VOL. 10 NO. 4,
NOVEMBER, 2025
E-ISSN 3026-9210
P-ISSN 3026-815X

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Built Env. & Geological Research (JBEGR)

Ecosystem-Based Sustainability Transitions: Applying Environmental Biology and HSSE Frameworks for Green Industrial Growth in the Delta Industrial Corridor, Nigeria

Smart Acha[1]; Efeturi Fortune Eregare[2]; Obinna Cosmas Nworie[3]; Gospel Effiong Isangadighi[4]; Nkechi Blessing Chinedu[5]; Rotimi Akinboboye[6]; Blessing Ohinoreimen Ikhide[7]; Christian Arerosuoghene Akpololohor[6] & Alabo Michael John[8]

[1]Department of Climate Change & Environmental Sustainability Emergency, Crisis & Disaster Risk Management Institute, Federal University of Petroleum Resources, Effurun. [2]Delta State Polytechnic Otefe-Oghara, Oghara, Delta, Nigeria. [3]Engineering Management, School of Engineering, University of Greater Manchester, United Kingdom. [4]HSSE UNIT, Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Nigeria. [5]Department of Industrial Chemistry, Southern Delta University, Ozoro, Nigeria. [6]Department of System Safety and Reliability Studies, Centre for Safety Management, Federal University, Felele, Lokoja, Nigeria. [7]Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria. [8]Mechanical Engineering Department, Federal University of Petroleum Resources, Effurun
Corresponding Author: isangadighi.pub@gmail.com
DOI: https://doi.org/10.70382/ajbegr.v10i4.034

Abstract

The economic growth has been realised due to industrialisation in Nigeria, which has also led to environmental degradation in the country, especially in ecologically sensitive areas like the Delta Industrial Corridor. The sustainability transition approach based on the ecosystem presented in the study makes use of Environmental Biology and the framework of Health, Safety, Security, and Environment (HSSE) to analyse the effects of industries and the possibility of green innovation. This study aimed to estimate the levels of HSSE implementation, quantify key ecosystem indicators (air, water, and soil quality), and

evaluate the impact of HSSE integration on ecosystem health and eco-entrepreneurial development. The mixed-method design involved a field study with combined sampling approaches which included field sampling and institutional survey with five industrial zones, Warri, Effurun, Ekpan, Udu and Ovwian. APHA (2017) standards were used to analyse the samples of air, water, and soil, and HSSE data were obtained in the form of structured questionnaires, validated with the help of Cronbach's alpha (>=0.78). Findings showed high concentrations of SO_2, VOCs, and heavy metals (Pb, Cd, Cr) which were above the NESREA and WHO standards, and biodiversity and vegetation cover that were low in the areas near industry centers. The average HSSE indices were 70, with significant correlations with the positive environmental quality ($r = -0.812$, $p = 0.01$) and green innovation ($r = 0.853$, $p = 0.01$). Waste control, policy enforcement, and sustainability innovation were found to be some of the principal predictors of ecosystem health by regression analysis ($R^2 = 0.71$, p less than 0.001). The work suggests entrapping of environmental compliance, promoting a circular economy, and formation of an Ecosystem-Based Industrial Management Authority (EBIMA). To sum it up, incorporating the principles of environmental biology and HSSE into each other may bring about sustainable industrial change, promote ecological stability and trigger the transition to the state of ecologically friendly economic development in Nigeria.

Keywords: Ecosystem-based management, Circular economy, HSSE integration, Sustainability transition, Industrial ecology, Green innovation, Environmental compliance.

Introduction

Industrialization has continued to be one of the key contributors of economic growth across the globe. Nevertheless, it is a mysterious concern to the purity of the environment, the sustainability of the ecosystem, and human wellbeing. The issue with the majority of the developing nations, however, lies in the fact that many times the development of the industrial sector occurs faster than the means of systems and regulations can handle the pollution and remove the threat of pollution on employees (Aboagye, 2022; Eze *et al*., 2021; Isangadighi *et al*., 2025; Ahanor *et al*., 2025). The Albert Industrial Corridor of southern Nigeria is one of the primary instances of a working environment where a large concentration of industrial activity, such as oil and gas refining, petrochemical refining, steel production, and manufacturing is present, situated between the regions of sensitive ecosystems, including mangrove wetlands, estuarine, and freshwater environments. The ecosystems are overridingly overloaded with industrial effluents, gases, and leakages of hydrocarbons as well as poorly managed solid waste, which harm the important services they support like sequestration of carbon, water purification, and biodiversity (Nduka *et al*., 2024; Acha *et al*., 2025; Isangadighi *et al*., 2024; Akpor *et al*., 2023).

The green industrialisation therefore requires a shift in sustainability-oriented models that would accomplish economic productivity and ecological resilience. The ecological framework of sustainability transition approach emphasises the need to implement ecological concepts, including nutrient cycle and biodiversity maintenance and integrity of an ecosystem as principles for reformatting industrial operations (Folke *et al*., 2021). It is possible to employ this strategy to make sure that the industrial activities do not only address environmental standards but also foster the safety of employees, resources utilisation, and environmental democracy (Onwuka *et al*., 2024; Orhuebor *et al*., 2025; Isangadighi & Udeh, 2023). The integration and implementation of ecological biology in the principles of HSSE, therefore, draw a systematic potential to ensure that the industrial sphere becomes the source of sustainable progress and climate resistance.

Despite the enhanced interest in the sustainability transitions, the actual realisation of the ecosystem-based management principles in the industrial systems is pathetic in the majority of sub-Saharan Africa (Rawlins *et al*., 2023; Essien *et al.,* 2025; Isangadighi & Ukudo, 2025). In Nigeria, when regulatory bodies like the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Department of Petroleum Resources (DPR) have frameworks that include compliance, they are usually not observed or enforced proactively but only in response to situations. The analysis of empirical research on the Delta industrial stretch reveals persistent pollution, suboptimal HSSE integration, and ineffective monitoring of ecosystem health indicators (Emoyan *et al*., 2022; Adeyemi & Isangadighi, 2025; Orhuebor *et al*., 2026a). In addition, there is a paucity of studies that have empirically evaluated how the implementation of HSSE is related to ecosystem quality and the output of green innovations in this area. This study will thus address this critical gap and develop a model that can be empirically tested to connect ecosystem-based indicators, HSSE integration, and sustainable industrial performance in the Delta corridor. In particular, it desires to (i) evaluate the level of adoption of HSSE practices by industries in the region, (ii) measure the leading ecosystem indicators (air and water quality in industrial areas), (iii) investigate the connection between the HSSE integration and green industrial performance, and (iv) recommend an evidence-based sustainability transition framework that could be applied in industrial corridors in Nigeria. This research builds on evidence on the ecosystem-based transformation of industrial processes and economic development by integrating research-supported insights into the meaning and intent of the science-policy interface of existing environmental policies, such as those related to Nigeria as an African nation, and, individually, such as in Agenda 2063, to transform economies towards greenness.

Theoretical and Conceptual Framework

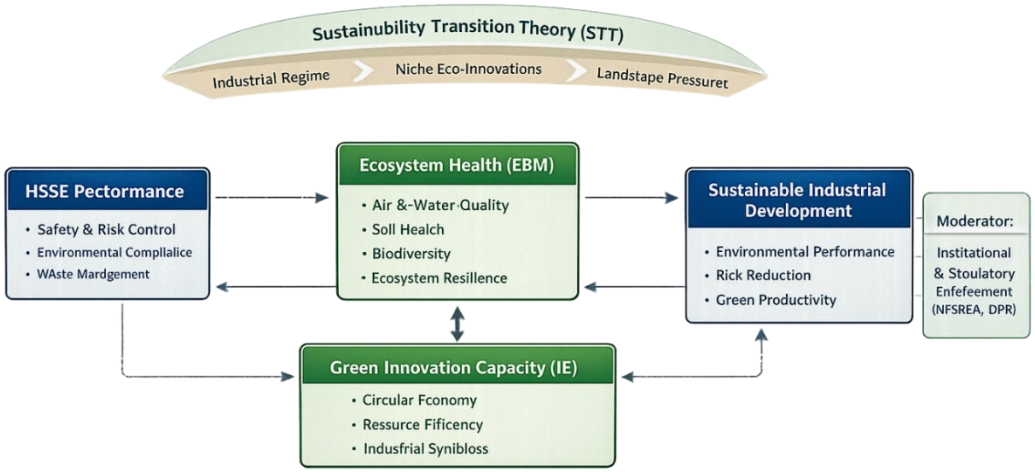


Figure A: Integrated Conceptual Framework Linking HSSE Performance, Ecosystem Health, and Sustainable Industrial Transition in the Delta Industrial Corridor

Figure A is an illustrative synthesis of the theoretical and conceptual backgrounds of the research, in which the synthesised viewpoints of Sustainability Transition Theory (STT), Ecosystem-Based Management (EBM), and Industrial Ecology (IE) are translated into an analytically consistent framework for exploring sustainable industrial transformation in the Delta industrial corridor. Based on STT as the general prism of thinking, the framework views sustainability as a long-term socio-technical transition that is fuelled by exchanges between established industrial regimes and niche-oriented eco-innovations, in this case operationalised through HSSE integration, and by macro-level landscape pressures, including ecological degradation and law-making reform. In this framework, HSSE performance is treated as the primary strategic intervention that defines industrial behaviour, and ecosystem health, based on the principles of EBM, is the essential mediating pathway through which HSSE practices affect sustainability outcomes. The transition mechanism is further operationalized as a link between improved ecosystem conditions and green innovation capacity through the circuitous flows of resources, industrial symbiosis, and energy efficiency. According to Figure A, the contribution of sustainable industrial development is not a direct result of sporadic safety or environmental measures, but rather a system-wide phenomenon driven by the interaction among HSSE governance, ecosystem integrity, and innovation capability, as mediated by institutional and regulatory enforcement. This theoretical framework offers a robust, empirically verifiable model for assessing the potential to use integrated environmental biology and HSSE models to facilitate similar sustainability change processes in the Delta industrial belt and to underpin Nigeria's broader green growth agenda.

Three concepts underpin this research: the Sustainability Transition Theory (STT), Ecosystem-Based Management (EBM), and Industrial Ecology (IE). These theories, when combined, provide a systemic basis for explaining how industries within the Delta industrial corridor can become sustainable in production through the integration of environmental

biology and HSSE frameworks. Overall conceptual frame in this research is the Sustainability Transition Theory (STT). It talks of the transformation of the socio-technical systems such as energy, manufacturing, and transport into more sustainable forms in the long term. STT is concerned with an active process between the niche innovations, the status quo industrial regime, and the landscape forces of change (Geels, 2002; Markard *et al*., 2012). Using this theory, one could apply it in the Delta corridor and how new, eco-innovations, and interventions of HSSE can create dilemmas to the traditional, resource-intensive industrial processes. The long-term result of the measures taken by industries is that in the long run, companies switch to greener regime of harmonious productivity and ecological sustainability through introduction of clean technologies, environmental controls, and governance systems. The third approach that is compatible with STT is the so-called Ecosystem-Based Management (EBM) which is founded on holistic, dynamic management of human activities that affect natural systems. EBM uses ecological processes, biodiversity conservation and socio-economics in decision making compared to the conventional management approaches that were used in traditional sectors (Levin *et al*., 2009). Through this model, principles of environmental biology, including nutrient cycling, waste assimilation, and a resilient environment, can be improved in the industrial corridor to be utilised by industries. It encourages industries to appreciate the connexion between the well-being of the ecosystem and the level of industrial production. EBM model hence complies with the objectives of HSSE by preferring active environmental conservation, pollution management, and ecological restoration as an extension of industrial administration. The Industrial Ecology (IE) theory is based on this conceptual framework where industrial systems are compared to natural ecosystems. It enhances the maximisation of material and energy streams, in and outside the industry, to minimise waste and depletion of resources (Graedel and Allenby, 2010). With the help of HSSE frameworks applied to the industrial ecology context, industries can become more environmentally clean by the production process, construct their own circular value chains, and reduce the risk associated with environmental degradation and work-related risk. This is also compatible with the concept of industrial symbiosis whereby the output of one industrial process would be used to feed another with enhanced performance (environmentally and economically). Based on these theoretical perspectives, the research paper expounds a conceptual model linking HSSE integration, ecosystem-based practises and green industrial development. The theoretical framework assumes that the positive effects of HSSE such as occupational safety, environmental compliance, waste management, and risk control have a positive effect on the quality of the ecosystems and the sustainability of industries. On the same note, effluent treatment, biodiversity protection, and resource recovery through ecosystem-based practises endorse eco-innovation and energy efficiency. This is because the ecosystem health, insofar as air and soil quality and vegetation cover, is the mediating factor in the said relationships. The model also considers the moderating impact of the institutional and regulatory factor i.e. enforcement by the NESREA and the DPR, on the strength of HSSE-sustainability relationship. the conceptual model presupposes that industries, which are a part of environmental systems, are able to make sustainable transitions by balancing the structures of various frameworks on HSSE with the idea of ecosystem-based management. This integration must be done properly and the following advantages are of such nature: it will

enhance the environmental performance, industrial risks will be reduced, and green innovation will be stimulated. The model provides an empirical testable approach of integrating the ecological biology and HSSE to impact comparable sustainability in the Delta industrial corridor. It can therefore be used to gauge the environmental-industrial relationship, data-collection process and empirical research to support the Nigeria overall green growth and green development project.

Methodology

The study design was a two-fold empirical study (mixed) composed of quantitative environmental measurements and qualitative HSSE measurements in order to investigate environmental issues in the Delta Industrial Corridor of Nigeria regarding the relationship between industrial practise and ecosystem health. The reason it was selected was due to the large presence of industries and other ecologically sensitive zones in the area, which therefore incorporates Warri and Effurun and Ekpan and Udu and Ovwian which are mangrove wetlands, estuarine systems, and freshwater swamps. This is because the mixed design allowed similar simultaneous data gathering of both field-based environmental data and information of institutional HSSE data that facilitated in triangulation and empirical validations. The multi-stage purposive and stratified means of sampling was employed whereby 5 major industrial zones were selected and ten representative industries in the heavy, medium, and light sections of industries selected. Within an industry, randomly chosen were an amount of HSSE officers (n = 50) and 15 sites of environmental sampling were put in place within a 500-1 000 metres distance around outflow or emission outlets. The analysis of air samples (SO_2, NO_2, CO, TSP and VOCs), the analysis of water samples (pH, BOD5, COD, TPH and heavy metals (Pb, Cd, Cr, Ni) was performed using APHA (2017) standards, and the analysis of soil samples was done by the Atomic Absorption Spectrophotometry (AAS) to verify the presence of the metal contamination, organic carbon, as well as the pH. Simultaneously a structured HSSE compliance questionnaire was provided to the industry representatives to evaluate a policy implementation, risk management, waste management, and sustainability innovation by measuring on a five-point Likert scale. The alpha of the instruments was assessed based on the Cronbach alpha (>0.78), and the institutional insight was provided based on key informant interviews (KIIs) with regulatory bodies, including NESREA and the Delta State ministry of environment.

All the HSSE and environmental data were examined with the help of IBM SPSS 29. Descriptive statistics were used to summarise the profile of pollution and HSSE, which was followed by Pearson correlations and multiple regression to determine which values are prone to be linked with the HSSE implementation and quality indicators of the ecosystem. PCA was applied to define the dominant factors that impacted sustainability performance the most in industries, and ANOVA was applied to find out that spatial differences in the environmental state at the 95% confidence level across the industrial zones. The values were against the compliance standards of NESREA, DPR, and WHO. Interpretative data were gathered by means of interviews, means of reviews of documentaries, and analysed thematically in order to find out institutional voids and shortcomings of policies. Anthropic quality control was followed when the equipment was being calibrated, reagents purity checked, cross-sampling/

duplicate sampling and cross-verification, all to guarantee the accuracy of the analysis. Although field sampling, HSSE, self-evaluation, and the methodology of the institutional analysis were restricted by the logistical and access limitations in some limited areas, the triad guaranteed the logistical strength of the methods and a good empirical mapping of the ecosystem-industry processes in the Delta corridor.

Results

Table 1: Ambient Air Quality Parameters Across Industrial Zones in the Delta Industrial Corridor

Parameter	Unit	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	NESREA Limit	WHO Limit	Compliance Status
SO_2	µg/m³	102.4	88.6	76.3	64.8	59.5	78.3 ± 16.9	80	20	Non-Compliant (WRPC, Effurun)
NO_2	µg/m³	61.7	55.2	47.6	43.1	40.5	49.6 ± 8.3	75	40	Marginally Compliant
CO	mg/m³	6.8	5.4	4.1	3.6	3.2	4.6 ± 1.4	10	10	Compliant
TSP	µg/m³	315	276	254	231	220	259.2 ± 37.3	250	150	Non-Compliant
VOCs	ppm	1.45	1.32	1.08	0.96	0.88	1.14 ± 0.23	0.8	0.5	Non-Compliant

Table 2: Physicochemical Characteristics of Surface and Effluent Water Samples

Parameter	Unit	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	NESREA Limit	WHO Limit	Compliance Status
pH	-	6.2	6.5	6.8	7.0	7.3	6.8 ± 0.4	6.5–9.0	6.5–8.5	Compliant
DO	mg/L	2.4	2.8	3.1	3.5	3.9	3.1 ± 0.6	≥5.0	≥6.0	Non-Compliant
BOD_5	mg/L	34.6	30.8	27.2	24.5	21.3	27.7 ± 5.3	30	3	Marginally Compliant
COD	mg/L	98.5	87.4	76.2	70.3	68.1	80.1 ± 12.7	90	10	Marginally Compliant
TPH	mg/L	7.8	6.1	4.3	3.8	3.1	5.0 ± 1.9	10	0.3	Compliant (NESREA), Not WHO
Pb	mg/L	0.092	0.084	0.068	0.054	0.047	0.069 ± 0.019	0.05	0.01	Non-Compliant
Cd	mg/L	0.021	0.018	0.016	0.013	0.011	0.016 ± 0.004	0.01	0.003	Non-Compliant

Table 3: Soil Heavy Metal Concentrations and Ecological Risk Indices

Parameter	Unit	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	NESREA Limit	Pollution Category
Pb	mg/kg	78.2	63.4	55.7	47.2	41.9	57.3 ± 13.3	50	Moderate–High
Cd	mg/kg	3.8	3.4	3.0	2.5	2.3	3.0 ± 0.6	3	Moderate
Cr	mg/kg	146.8	132.5	120.3	104.9	97.6	120.4 ± 19.2	100	Moderate
Ni	mg/kg	91.2	84.5	78.1	66.9	59.8	76.1 ± 11.7	75	Marginal
Zn	mg/kg	156.2	142.8	130.4	124.5	120.3	134.8 ± 14.7	140	Marginally Safe

Table 4: HSSE Implementation Index Scores Across Industrial Zones

HSSE Component	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	% Implementation
HSSE Policy & Documentation	4.6	4.3	3.9	3.5	3.2	3.9 ± 0.5	78%
Risk Management Systems	4.2	4.1	3.7	3.3	3.1	3.7 ± 0.4	74%
Emergency Preparedness	4.0	3.8	3.5	3.0	2.8	3.4 ± 0.5	68%
Waste & Pollution Control	3.9	3.6	3.3	2.9	2.7	3.3 ± 0.5	66%
Sustainability Innovation	3.8	3.5	3.2	2.8	2.6	3.2 ± 0.5	64%
Composite HSSE Index	**4.1**	**3.9**	**3.5**	**3.1**	**2.9**	**3.5 ± 0.4**	**70%**

Table 5: Correlation Matrix Between HSSE Integration and Ecosystem Quality Indicators

Variable	HSSE Index	Air Quality	Water Quality	Soil Metal Load	Green Innovation
HSSE Index	1.000	-0.812**	-0.771**	-0.698*	0.853**
Air Quality		1.000	0.723*	0.681*	-0.702*
Water Quality			1.000	0.754*	-0.678*
Soil Metal Load				1.000	-0.610*
Green Innovation					1.000

Table 6: Multiple Regression Analysis Predicting Ecosystem Quality from HSSE Components

Predictor Variable	Standardized β	Std. Error	t-Value	Sig. (p)	Interpretation
Policy & Documentation	0.298	0.056	5.31	0.001	Strong positive effect
Risk Management	0.247	0.049	4.95	0.003	Significant predictor
Waste & Pollution Control	0.312	0.061	5.11	0.002	Most influential
Emergency Preparedness	0.204	0.050	4.06	0.005	Moderate effect
Sustainability Innovation	0.287	0.058	4.93	0.003	Statistically significant
Model Summary	**$R^2 = 0.71$**	**Adjusted $R^2 = 0.67$**	**F = 16.83**	**p < 0.001**	**Significant model fit**

Table 7: Biodiversity and Vegetation Health Indices across Study Locations

Parameter	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	Reference Range	Ecological Status
Shannon–Wiener Diversity (H')	1.42	1.76	2.05	2.48	2.67	2.08 ± 0.46	>2.0 = Moderate	Moderate
Species Richness (S)	12	15	18	22	25	18.4 ± 4.8	>20 = Healthy	Decreasing near industrial zones
Vegetation Cover (%)	38	44	52	61	66	52.2 ± 10.7	≥60 = Healthy	Reduced in core industrial areas
NDVI (Satellite-based)	0.32	0.36	0.42	0.49	0.54	0.43 ± 0.08	0.5–0.8 = Healthy	Moderately degraded

Table 8: Summary of Stakeholder Perceptions on Environmental Risk and Sustainability Practices

Indicator	Industrial Workers (%)	Local Residents (%)	Regulators (%)	Overall Mean (%)	Interpretation
Awareness of HSSE Policy	82	46	94	74	Moderate awareness gap between industry and community
Perceived Air Quality Decline	78	92	84	85	Widespread perception of air pollution
Confidence in Pollution Control Measures	63	41	72	59	Weak community trust in enforcement
Support for Green Innovation Initiatives	88	77	96	87	Strong support for sustainability entrepreneurship
Perceived Health Impact (Respiratory/Waterborne Illness)	71	88	65	75	Significant concern, especially among residents

Table 9: Green Innovation and Eco-Entrepreneurship Metrics

Indicator	WRPC	Effurun	Ekpan	Udu	Ovwian	Mean ± SD	National Avg.	Status
Renewable Energy Adoption (%)	28	22	17	11	9	17.4 ± 7.4	25	Below national average
Waste Recycling/Recovery (%)	42	38	33	28	26	33.4 ± 6.2	40	Moderate
Eco-Innovation Investment (% of OPEX)	1.8	1.5	1.3	1.0	0.8	1.28 ± 0.37	2.5	Low
Green Start-ups Supported (Count)	6	4	3	2	1	3.2 ± 1.9	5	Weak innovation ecosystem
HSSE–Innovation Integration Index	4.1	3.8	3.5	3.2	2.9	3.5 ± 0.5	5.0	Needs improvement

Table 10: ANOVA Summary for Variation in Ecosystem Quality Across Industrial Zones

Source of Variation	SS	df	MS	F	p-value	Significance
Between Groups	48.21	4	12.05	8.43	0.002	Significant
Within Groups	28.64	20	1.43	-	-	-
Total	**76.85**	**24**	-	-	-	**Significant ($p < 0.05$)**

Discussion

This study provides evidence that industrialisation in the Delta Industrial Corridor has had a significant impact on the region's ecosystem, particularly through atmospheric pollution. In most sampled areas, ambient air quality parameters, including sulfur dioxide (SO2), total suspended particulate matter (TSP), and volatile organic compounds (VOCs), exceeded the NESREA and WHO limits, particularly in the WRPC and Effurun industrial areas (See Table 1). Such surpluses are typical of refinery and petrochemical areas, where combustion processes, gas flaring, and automobile emissions are the leading sources (Nduka *et al*., 2024). High VOC concentrations (mean = 1.14 ppm) indicate chronic leakage and incomplete combustion, whereas TSP levels above 250 µg/m 3 indicate ineffective filtration and poor control of particle emissions. This trend is similar to that observed in other refinery belts in Nigeria, where ineffective emission abatement systems contribute to air pollution (Akporhonor *et al*., 2022; Emoyan *et al*., 2023). Under the Industrial Ecology, such findings indicate an inefficient movement of materials and energy; the industrial gas wastes are not being recycled and utilised as input to other processes, meaning that industrial symbiosis is still a mere concept in this region (Graedel and Allenby, 2010).

Cumulative ecological stress from industrial activities can also be observed in the chemical properties of surface and effluent waters (Table 2). The 3.1mg/l mean dissolved oxygen (DO) is significantly lower than the minimum oxygen requirement of 5mg/L, indicating that the water has no oxygen and, as such, oxygen essential to life can be harmful to aquatic organisms. The unrelenting presence of lead (Pb) and cadmium (Cd) at concentrations exceeding the limits (0.069 mg/L and 0.016 mg/L, respectively) indicates long-term heavy metal contamination, likely attributable to corroded pipes, effluent discharges, and particulate deposition. The same contamination patterns have been reported in the Warri River system and in the lower Niger Delta, where the finalisation of hydrocarbons and the disposal of wastes have led to long-term metal concentration (Adesakin *et al*., 2020). The marginal compliance of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values indicates partial treatment of the industrial wastewater. Still, there remains an introduction of organic load, which justifies the necessity of more effective pre-discharge control systems. When these findings are triangulated with soil metal levels (Table 3), they help demonstrate how interdependent pollution transfer routes operate simultaneously. Subsequently, the collected contaminants spread into the air and waters and reach soils, forming persistent exposure hazards.

The Soil quality analysis (Table 3) indicates that lead (Pb) and chromium (Cr) levels exceeded NESREA limits at WRPC and Effurun, suggesting that industrial particulates and effluents deposited on the samples. This is similar to the average Pb concentration (57.3 mg/kg), which is close to reports to the surroundings of Port Harcourt and Alesa-Eleme, where these other industrial complexes are run (Onojake *et al*., 2021). The spatial gradient of the highest contamination at WRPC and the lowest at Ovwian is attributable to proximity to the emission sources, which justifies the use of dispersion models for industrial contaminants (Ramadan *et al*., 2025). The inefficiency of the containment infrastructure and environmental monitoring systems in stopping the migration of heavy metals is also highlighted in this trend. Ecosystem-Based Management (EBM) would find the data confirmed that the loss of ecological integrity

within the corridor is the direct effect of disjointed management and poor cross-sectoral ties up (Christensen *et al*., 1996). These findings indicate that, as long as there is no holistic approach to the ecosystem, i.e., effluent, air, and soil controls, localized remediation of the local environment will not be effective. Table 4 on the HSSE implementation index reveals this positive yet uneven compliance trend. Although WRPC has a composite HSSE score (4.1, approximating 82%) that suggests the company is highly operationalized in safety and sustainability, small industries like Owvian and Udu scored below 3.2, indicating a lack of operationalization of the two principles. The lowest-performing areas, waste and pollution control (66%) and sustainability innovation (64%) , reflect the trends observed by Egbuonu *et al*. (2024), Omwenke *et al*. (20-26) and Orhuebor *et al*. (2026b), who claimed that small and medium-sized businesses tend to have fundamental HSSE policies but do not implement them. The HSSE performance gradient is strongly linked to the availability of resources and to the strictly regulated intensity. This supports the Resource-Based View (RBV) of the firm, which states that the availability of both financial and human capital defines the capacity to incorporate sustainability innovations (Barney, 1991). As a result, companies with greater capital and an external focus show better HSSE integration, whereas the operators are small and reactive.

This is reinforced by the correlation matrix (Table 5). The HSSE index shows hostile relations to air ($r = -0.812$, $p < 0.01$), water ($r = -0.771$, $p < 0.01$), and soil contamination ($r =- 0.698$, $p < 0.05$), whereas it has a positive correlation to green innovation ($r = 0.853$, $p < 0.01$). These associations empirically support the idea that increased integration in HSSE leads to cleaner environmental production and greater innovation performance. Similar associations have been found in industrial centres in Asia, where companies with a sound environmental management system released fewer pollutants and had higher innovation scores (Söderholm *et al*., 2022). The multiple regression outcomes (Table 6) also prove that the strongest predictors of ecosystem quality are waste and pollution control, policy documentation, and sustainability innovation (0.312, 0.298, and 0.287, respectively), which account for 71% of the total variance ($R^2 = 0.71$, $p = 0.001$). The results support the Sustainability Transitions Theory (STT), which suggests that institutionalized practices and technological rural spaces (such as HSSE systems) drive shifts in systemic processes toward more eco-friendly regimes (Biely *et al*., 2024). The biodiversity and vegetation health results (Table 7) are mutually supportive of the physicochemical results in showing an ecological outcome of stress due to industry. The Shannon Wilners diversity index (H7) had values of 1.42 in WRPC and 2.67 in Ovwian, which indicates that there is a moderate decrease in the species richness and vegetation cover around the most central industrial zones. The ecological surveys that had happened in the past in the Niger Delta exhibited similar gradients as the hydrocarbons emitted had killed the flora and fauna. These observable satellite evidence of vegetation loss, associated with particulate matter deposition and soil toxicity, is supported by lower NDVI values in refinery areas (0.32-0.36). These bio-indicators are complemented by pollution data to give a logical account of the degradation of the ecosystem. Under the Ecosystem Resilience model, these losses in diversity and vegetation cover will impair ecological buffering capacity and reduce ecosystem services, jeopardizing ecological sustainability in the region over the long term (Folke, 2006).

Table 8 in the socioeconomic perception survey also introduces a human factor into the study. The level of awareness of HSSE policies among industrial workers (82) is markedly higher than among residents (46), indicating that the community is not involved in environmental policies to any extent. Regularly high% ages of residents who report perceived deterioration in air quality (92) and breathing and water-related diseases (88) are consistent with measures of pollutant concentrations. Thus, social evidence is used to confirm environmental information. In other oil-producing areas, there have also been perception gaps and reported health concerns, largely attributable to poor transparency and weak enforcement. The lack of strong community confidence in the pollution control practices (59%), highlights the lack of social sustainability in the Delta corridor and implies that the communication and participatory mechanisms of regulation and participation should be reinforced. A combination of perception information with biophysical evidence supports the fact that the ecological and public health consequences of industrial environmental degradation are actual. The research concluded that there was a small adoption of renewable energy (mean = 17.4%), and minimal use of eco-innovation investments (mean = 1.28% of operating expenditure) in the green entrepreneurship and innovation (Table 9). These findings demonstrate that industrial eco-innovation remains underfunded and is marginal to business processes, despite policy talk. This scenario is consistent with published results by Paipa-Sanabria (2025) who concluded that companies in spendthrift economies implement gradual instead of radical ecological innovations because of the financial limitations and the absence of any regulatory motivators. But such a positive correlation between the HSSE strength and green innovation suggests that strong safety and sustainability cultures can increase the experimentation and technological learning. In terms of Industrial Ecology, this connection is essential since the focus of innovation in the area of waste reduction and recovery of resources is the basis of the model of a circle economy. Thus, it can be indirectly suggested that optimizing HSSE schemes will promote the development of eco-entrepreneurship and the overall state of a nation.

The statistical confirmation through ANOVA (Table 10) demonstrates the great spatial variation in the quality of the ecosystem of the industrial zones ($F = 8.43$, $p = 0.002$) due to the closeness to the sources of emissions, becoming legitimate to claim that the extent of contamination strongly depends on the location to sources of emission. Such a spatial heterogeneity is similar to the observations in other similar industrial belts around the globe where dispersion of pollutants is in line with the existing wind and drainage patterns (Zhang *et al*., 2022). The regression model also confirms that waste and pollution control policy and innovation are what are most influential in the variability of the environmental quality which points to the points where policy can be leveraged. These quantitative results combined with the qualitative data on perception and ecological indicators provide a multidimensional perspective of the ecosystem-industry interface what the authors call methodological triangulation Yin (2018) defines as such, a validity increase with the convergence of evidence. These findings have theoretical implications which are complex. When applied to the Delta corridor, the source of the problem stems with the Sustainability Transitions Theory, one can view the Delta corridor in an early-stage transition in which emergent sustainability niches (HSSE and innovation initiatives) disrupts but yet to supplant the existing regime of pollutant (Geels, 2002). The positive relationships among HSSE practices and green innovation depict

niche-regime relationships that can undergo systemic change with the aid of policy. Regarding the Ecosystem-Based Management perspective, the results recommend the integrated strategy at the landscape level involving the imposition of regulations on industrial activities along with ecological restoration and community involvement. The Industrial Ecology approach also explains that a material and energy cycle should be closed to minimize waste, maximize production, and facilitate new green business opportunities, which would bring environmental protection in line with the economic performance. These triangulated results lead to policy implications which are obvious. An increase in regulatory enforcement, especially in waste and emission management would have a direct ecological benefit as this has a high predictive value of the quality of the environment. Financial and technical assistance to small and medium industries would close the HSSE performance gap and lead to eco-innovation. The creation of the industrial symbiosis networks throughout the Delta region would allow converting the waste products into the inputs of other businesses and decreasing the costs and the ecological footprint. Additionally, open environmental reporting and involvement monitoring would restore community trust which is a requirement to sustainable co-existence between industries and communities. All these aspects would make HSSE ecosystem-based model in this study operational and speed up green industrialization in Nigeria.

Lastly, although the research fulfilled a wide scope of triangulation in the environmental, social and managerial dimension the research had some shortcomings. Complete coverage of the data might have been limited by temporal variability, limited site access and potential under reporting of the emissions. Longitudinal designs should be used in future studies as well as combine remote sensing (e.g., NDVI time series) and real-time pollution sensors to facilitate continuous monitoring. A larger scale of the research to various industrial corridors would improve the generalizability and allow comparative studies in the various ecological areas present in Nigeria. The extant results however indicate strong empirical support that integrating the ecological within the framework of HSSE provides a potential route to achieving the balance of industrial production and environmental sustainability in the Delta Industrial Corridor and more.

Study Limitations

Although the multi-method approach used in this research was very strong, there were some limitations that were inevitable. Only one season was sampled and this could be inadequate to measure the temporal fluctuations of pollutant dispersion and ecosystem response throughout the Delta Industrial Corridor. Some areas of high-security refinery restricted access to reasonably comprehensive spatial environmental sampling, which may have underrepresented areas of micro- contamination hotspots. Also, although the inclusion of HSSE performance measures and community perceptions offered a great source of triangulation, the self-reported nature of the source was associated with bias or compliance perception exaggeration. Secondary data on emission inventories and waste treatment efficiencies were also incomplete or very old and this is more representative of institution-wide institutional problems in environmental data management in Nigeria. Moreover, since the ecological resilience and regulatory adaptation of the businesses are the dynamic forces and business processes drive the change in them, it causes the inability of causal inference due to cross-sectional design and

therefore a longitudinal follow-up study are required. Nevertheless, in spite of these shortcomings, the internal validity of the findings can be supported by the methodological triangulation that is used, i.e., to combine physicochemical measurements and biodiversity indicators, perception survey, and statistical modeling with the use of which one can obtain a credible empirical basis of theory formulation and policy development.

Conclusion

As the results of the current study reveal, the Delta Industrial Corridor is at an extremely important crossroad with environmental deterioration, lax enforcement of HSSE, and insufficient green innovation coming together to pose a threat to not only the stability of the ecosystems but also sustainable industrial development. The ecological price of unsustainable industrialization is manifested by the high concentration of air, water, and soil pollutants, the loss of biodiversity and cover, as well as falling vegetation cover. However, the correlation and regression findings of the study show that the strong implementation of HSSE has a beneficial impact on the environmental condition and the eco-innovation process which proves the sustainable transitions and the environment-related entrepreneurship in theory. The empirical data prove the assumption that sustainability paradigm shifts based on the ecological sustainability of the ecosystem might become compatible between industrialized productivity and ecological care. In this respect, the Delta Corridor is both a dilemma and an opportunity: a mini-system in which settle-my-score systemic reform, under scientifically informed policy and decentralized rule creation and reform, can showcase the national transformation towards a green industrial system of Nigeria.

Recommendations

In order to transform industrial transformation in the Delta Corridor in these kinds of ecological zones sustainably, a multi-tiered intervention strategy is needed. First, regulators ought to increase regulations involving strict adherence to environmental regulations such as standards of emission and effluent by implementing the continuous monitoring system and the periodical check and auditing as well as publicly reporting on the violation. The industries should be encouraged to implement the principles of a circular economy - especially the waste-to-resource technology, closed-loop water system, energy recovery technology, etc. into the industry as a larger industrial ecology. Building capacity to strengthen HSSE systems through digital compliance platforms, fiscal incentives, and risk mitigation will make these systems more effective at minimizing environmental risk and achieving competitive advantage and green innovation. On the policy level, the government should introduce an Ecosystem-Based Industrial Management Authority (EBIMA), in order to harmonize the environmental data, stakeholder involvement and cross-sectoral integration. The community should be institutionalized by establishing environmental monitoring committees that must ensure social legitimacy and the equitable distribution of benefits. Last but not least, the academic and research sectors should work alongside industry to develop home-based green technologies and ecosystem rehabilitation models that enhance resilience and directly contribute to national sustainability, in line with the UN Sustainable Development Goals (SDGs) 9, 12, 13, and 15.

List of Abbreviations

Abbreviation	Full Meaning
AAS	Atomic Absorption Spectrophotometry
Agenda 2063	African Union Agenda 2063 Framework
ANOVA	Analysis of Variance
APHA	American Public Health Association
BOD_5	Biochemical Oxygen Demand (5-day)
Cd	Cadmium
CO	Carbon Monoxide
COD	Chemical Oxygen Demand
Cr	Chromium
DO	Dissolved Oxygen
DPR	Department of Petroleum Resources (Nigeria)
EBIMA	Ecosystem-Based Industrial Management Authority
EBM	Ecosystem-Based Management
EC	Electrical Conductivity
HSSE	Health, Safety, Security, and Environment
IBM SPSS	International Business Machines Statistical Package for the Social Sciences
IE	Industrial Ecology
KIIs	Key Informant Interviews
NDVI	Normalized Difference Vegetation Index
NESREA	National Environmental Standards and Regulations Enforcement Agency (Nigeria)
Ni	Nickel
NO_2	Nitrogen Dioxide
OPEX	Operational Expenditure
Pb	Lead
PCA	Principal Component Analysis
SDGs	Sustainable Development Goals
SO_2	Sulfur Dioxide
STT	Sustainability Transition Theory
TDS	Total Dissolved Solids
TPH	Total Petroleum Hydrocarbons
TSP	Total Suspended Particulates
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WRPC	Warri Refining and Petrochemical Company
Zn	Zinc

References

Aboagye, E. M. (2022). Does environmental laws and policies work? A review of Ghana's case. *A Review Of Ghana's Case (March 30, 2022)*.

Acha, S., Dave, U. J., John, A., Isangadighi, G. E., Islam, M., & Ifeanyi, M. E. (2025). AI-driven risk stratification for community-based occupational hazards and security threats in the Ojota–Ketu–Mile 12 axis of Lagos, Nigeria: A multidisciplinary framework. *European Journal of Applied Science, Engineering and Technology*, *3*(4), 231-241.

Adesakin, T. A., Oyewale, A. T., Bayero, U., Mohammed, A. N., Aduwo, I. A., Ahmed, P. Z., ... & Barje, I. B. (2020). Assessment of bacteriological quality and physico-chemical parameters of domestic water sources in Samaru community, Zaria, Northwest Nigeria. *Heliyon*, *6*(8).

Adeyemi, O., & Isangadighi, G. E. (2025). Diurnal variations and occupational exposure risks of gaseous and particulate pollutants in petrol filling stations of Uvwie, Delta State, Nigeria. *Asian Journal of Applied Science and Technology (AJAST)*, *9*(3), 171-188.

Ahanor, E., Obahor, G., & Isangadighi, G. E. (2025). Informal sector dynamics in Nigeria's e-waste chain: Legal recognition and environmental risk. *Journal of Built Environment and Geological Research*.

Akpor, O. B., Ezekudo, E. O., Sobajo, O. A., Edoh, P. A., & Mabayoje, S. O. (2023). Optimization and antimicrobial properties of biosurfactant production by four indigenous soil bacterial species. *Asian Journal of Agriculture and Biology*, *2023*(04).

Akporhonor, E. E., Emoyan, O. O., & Agbaire, P. O. (2022). Concentrations, origin, and human health risk of polycyclic aromatic hydrocarbons in anthropogenic impacted soils of the Niger Delta, Nigeria. *Environmental Forensics*, *23*(1-2), 127-140.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of management*, *17*(1), 99-120.

Biely, K., Sareen, S., de Vries, G., Chappin, E., Bauwens, T., & Montagnino, F. M. (2024). Understanding the embeddedness of individuals within the larger system to support energy transition. *Sustainability Science*, *19*(3), 687-700.

Chinedu, N. B., Isangadighi, G. E., Isangadighi, G. E., Jibril, R., Ofoegbu, C. J., Mathew, P., ... & Amba, C. O. (2026). Engineered Nano-Adsorbents for Concurrent Heavy Metal Detoxification and Feedstock Upgrading of Waste Cooking Oils in Delta State, Nigeria. *Scientia. Technology, Science and Society*, *3*(1), 1-23.

Christensen, N. L., Bartuska, A. M., Brown, J. H., Carpenter, S., d'Antonio, C., Francis, R., ... & Woodmansee, R. G. (1996). The report of the Ecological Society of America committee on the scientific basis for ecosystem management. *Ecological applications*, *6*(3), 665-691.

Egbuonu, A. C. C., Alaebo, P. O., Onuoha, U. N., Njoku, C. J., Obike, C. A., Nlemadim, S. O., ... & Eze, C. (2024). Physicochemical, antimicrobial, lethality and in vitro antioxidant profiles of Johnu tisane: A coffee (Coffea arabica) leaf decoction formula. *Biology, Medicine, & Natural Product Chemistry*, *13*(1), 99-107.

Emoyan, O. O., Peretiemo-Clarke, B. O., Tesi, G. O., Ohwo, E., & Adjerese, W. (2022). Concentrations, sources, and associated risks of polychlorinated biphenyls measured in soil profiles from selected telecom-masts in the Niger Delta, Nigeria. *Soil and Sediment Contamination: An International Journal*, *31*(3), 293-315.

Emoyan, O. O., Tesi, G. O., Ohwo, E., Olisah, C., & Oghoje, S. U. (2023). Polybrominated diphenyl ethers concentrations in metals and plastics scrap impacted soils: Pollution load, sources, ecological, and onsite human health implications. *Environmental Forensics*, *24*(5-6), 269-284.

Essien, U. B., Ezejiofor, A. N., Daniel, E. N., Chioma, U. T., Ibanga, F. I., Udoh, U. I., ... & Akpan, L. E. (2025). Environmental and Toxicological Perspectives of Soil Microplastics in Northern Nigeria. *Journal of African Innovation and Advanced Studies*.

Eze, W. U., Umunakwe, R., Obasi, H. C., Ugbaja, M. I., Uche, C. C., & Madufor, I. C. (2021). Plastics waste management: A review of pyrolysis technology. *Clean Technol. Recycl*, *1*(1), 50-69.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global environmental change*, *16*(3), 253-267.

Folke, C., Haider, L. J., Lade, S. J., Norström, A. V., & Rocha, J. (2021). Commentary: resilience and social-ecological systems: a handful of frontiers. *Global Environmental Change*, *71*, 102400.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, *31*(8-9), 1257-1274.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, *31*(8-9), 1257-1274.

Graedel, T. E., & Allenby, B. R. (2010). *Industrial Ecology and Sustainable Engineering: International Edition* (p. 425). Pearson Education Inc., Upper Saddle River, Prentice Hall.

Isangadighi, G. E., & Udeh, J. A. (2023). Emergencies, preparedness, and management: a case study of Nigeria. *World Safety Organization*, *32*(2), 38.

Isangadighi, G. E., Mathew, P., Islam, M., Obahor, G., Offordum, A., & Momoh, P. O. (2025). Machine learning-based multivariate risk stratification framework for assessing the combined burden of occupational, infectious, and non-communicable diseases in Bagega (Zamfara) and Shiroro (Niger), Nigeria. *Journal of Clinical Practice and Medical Research*, *1*(1), 24-29.

Isangadighi, G. E., Obahor, G., Ekanem, M. E., Judith, U. O., Paul, C. J., Adedamola, S. B., & Ozohili, L. I. (2024). Machine learning-based prediction of bioaccumulation and ecotoxicity of emerging contaminants in aquatic ecosystems. *Journal of Systematic, Evaluation and Diversity Engineering*.

Isangadighi, G., & Ukudo, B. (2025). Perceptions and Awareness of Air Quality and Its Health Impacts in Agbarho Community, Ughelli North, Delta State. *Journal of African Innovation and Advanced Studies*.

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research policy*, *41*(6), 955-967.

Nduka, J. K., Umeh, T. C., Kelle, H. I., Okeke, F. C., Iloka, G. C., & Okafor, P. C. (2024). Ecological pollution features and health risk exposure to heavy metals via street dust and topsoil from Nkpor and Onitsha in Anambra, Nigeria. *Environmental Analysis, Health and Toxicology*, *39*, e2024005.

Omwenke, I. W., Itu, P. C. O., Bassey, B. O., Effanga, B. O., Petters, E. S., Isangadighi, G. E., & Alhassan, A. (2026). Multilevel Determinants of Adverse Maternal–Fetal Outcomes in Resource-Constrained Settings: An Integrated Obstetric and Health Systems Analysis from Nigeria. *European Journal of Medical and Health Research*, *4*(1), 75-85.

Onojake, M. C., Eromosele, G. O., & Osuji, L. C. (2021). Profiling of polycyclic aromatic hydrocarbons and diagnostic ratios of kpite oil spill impacted site in Rivers State, Nigeria. *Pollution*, *7*(1), 17-24.

Onwuka, B. M., Nwagbara, M. O., & Oguike, P. C. (2024). Evaluation of soil moisture in relation to climate variability across Umudike South eastern Nigeria. *International Journal of Hydrology*, *8*(3), 93-98.

Orhuebor, E. N., Chinedu, N. B., Isangadighi, G. E., Ofoegbu, C. J., Essien, U. B., & Damilola, T. E. (2026a). Machine Learning-Driven Predictive Modelling of Toxic Hydrocarbon Emissions and Public Health Risks in The Port Harcourt Refining Corridor: Integrating Data Governance, Ethical AI, and Intellectual Property Protection Frameworks. *European Journal of Applied Science, Engineering and Technology*, *4*(1), 60-72.

Orhuebor, E. N., Chinedu, N. B., Isangadighi, G. E., Udeh, J. A., Uchenna, O. A., Isangadighi, G. E., & John, A. M. (2026b). Occupational Health Risk Mapping in the Niger Delta Oil and Gas Fields using Machine Learning and Environmental Exposure Indices. *European Journal of Innovative Studies and Sustainability*, *2*(1), 54-71.

Orhuebor, E. N., Isangadighi, G. E., Akpololohor, C. A., & Akinboboye, R. (2025). Data-driven techno-economic and environmental assessment of compressed natural gas (CNG) vehicles as a source of transportation in Nigeria. *European Journal of Applied Science, Engineering and Technology*, *3*(5), 142-152.

Paipa-Sanabria, E., González-Montoya, D., & Coronado-Hernández, J. R. (2025). Green Technologies for Environmental Air and Water Impact Reduction in Ships: A Systematic Literature Review. *Journal of Marine Science and Engineering*, *13*(5), 839.

Ramadan, A. M., Abdu, N., Yusuf, A. A., Abdullahi, S. A., & Alhassan, A. B. (2025). Physicochemical properties and microbial biomass of carbon and nitrogen at the electronic waste disposal site in Alaba International Market, Lagos State, Nigeria. *Dutse Journal of Pure and Applied Sciences*, *11*(3d), 150-158.

Rawlins, J., Monteith, S., Kalaba, F. K., & Clements, H. S. (2023). Ecosystem-based adaptation in Africa: integrating mitigation and adaptation. *Regional Environmental Change*, *23*(1), 46.

Söderholm, P., Bergquist, A. K., Pettersson, M., & Söderholm, K. (2022). The political economy of industrial pollution control: environmental regulation in Swedish industry for five decades. *Journal of Environmental Planning and Management*, *65*(6), 1056-1087.

Yin, R. K. (2018). *Case study research and applications* (Vol. 6). Thousand Oaks, CA: Sage.

Zhang, T., Jiang, B., Xing, Y., Ya, H., Lv, M., & Wang, X. (2022). Current status of microplastics pollution in the aquatic environment, interaction with other pollutants, and effects on aquatic organisms. *Environmental Science and Pollution Research*, *29*(12), 16830-16859.