British Journal of Agroecology and Environmental Studies

DOI: 10.61424/bjaes
Journal Homepage: www.bluemarkpublishers.com/index.php/BJAES

BJAES
BLUEMARK PUBLISHERS

| RESEARCH ARTICLE

Transformative Strategies for Environmental Resilience: Implementing Circular Economy Principles to Address Plastic Pollution and Industrial Emissions in Greater Asaba

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| ABSTRACT
This study looks at transformational environmental resilience methods that use Circular Economy (CE) concepts to manage rising plastic pollution and industrial emissions in Nigeria's Greater Asaba area. Using a stratified random sample strategy, 418 respondents or 0.1% of the total population were surveyed using a mixed-methods approach that included structured questionnaires and semi-structured interviews. Quantitative data were analysed using SPSS v27, which included descriptive statistics, Pearson's correlation, and multiple regression analysis, while qualitative insights were coded thematically. The findings show that environmental resilience and CE adoption are significantly positively correlated ($r = 0.742$, $p < 0.01$), and that 61% of the variation in pollution reduction can be explained by CE interventions (R2 = 0.61). The results show that eco-design rules, closed-loop manufacturing, and waste valorisation significantly reduce the amount of plastic waste generated and industrial carbon emissions. The respondents cited a lack of public awareness, policy enforcement deficiencies, and infrastructure limitations as the main obstacles to CE inclusion. In order to integrate CE policies into urban environmental governance, the study emphasises the need for multi-stakeholder engagement that connects local communities, businesses, and municipal authorities. The study comes to the conclusion that targeted CE frameworks, supported by technical advancement and regulatory incentives, provide Greater Asaba a feasible option to reduce pollutant loads measurably while promoting socioeconomic co-benefits. This study provides a reproducible paradigm for other quickly urbanising African cities and adds factual support to the expanding conversation on CE as a tool for sustainable urban change.

| KEYWORDS

Circular Economy, Environmental Resilience, Plastic Pollution, Industrial Emissions, Greater Asaba.

| ARTICLE INFORMATION

ACCEPTED: 09 August 2025 **PUBLISHED:** 19 September 2025 **DOI:** 10.61424/bjaes.v2.i1.399

1. Introduction
Urban centres across sub-Saharan Africa face reinforcing crises of plastic leakage, deteriorating air quality, and climate-relevant industrial emissions that threaten public health, biodiversity, and economic vitality. Greater Asaba—an emergent metropolitan zone bridging the Niger River corridor and energy-intensive industrial clusters in Delta State—exemplifies this nexus. Recent satellite-based analyses comparing Asaba and Warri (2019–2024) reveal rising tropospheric NO_2 columns and spatially persistent hotspots linked to transport and point-source combustion, underscoring the inadequacy of linear “take–make–waste” models in rapidly urbanizing contexts (Amaechi, Aghe, & Okoduwa, 2025). Concurrently, Nigerian rivers show measurable ecological degradation from urban effluents and mismanaged plastics, with macroinvertebrate community shifts and water-quality exceedances reported even in federal capital waterways (Arimoro et al., 2024; Onyemenam, 2025). These patterns demand systemic, locally

adapted strategies that simultaneously curb material throughput and emissions while strengthening social and ecological resilience.

Circular economy (CE) principles—designing out waste and pollution, keeping materials in circulation, and regenerating natural systems—offer a coherent framework to align pollution control with competitiveness and livelihood security. However, recent scholarship cautions that CE transitions must be contextually embedded, equity-oriented, and participatory to avoid techno-centric pitfalls and rebound risks (Agostinho, De Kock, Giannetti, Almeida, & Zucaro, 2025). In the Global South, where informal recovery networks, heterogeneous infrastructure, and fiscal constraints shape waste governance, transformative CE pathways hinge on inclusive coalitions that mobilize cleaner production, industrial symbiosis, and social innovation across value chains (Agostinho et al., 2025; Oni et al., 2022).

Nigeria's evolving policy landscape the Climate Change Act (2021) and associated institutional reforms creates a window for integrating CE into subnational air-quality management, producer responsibility, and urban services (Olujobi, 2024). Yet operational guidance remains thin for mid-sized cities like Asaba, where cross-river trade, logistics, and small-to-medium industries amplify plastic demand and combustion emissions. Empirical evidence from Delta State indicates that particulate and NOx burdens co-vary with industrial activities and mobility patterns, calling for place-specific interventions that couple demand-side material strategies with supply-side process redesign (Amaechi et al., 2025).

This study addresses these gaps by examining "Transformative Strategies for Environmental Resilience" that implement CE principles to confront plastic pollution and industrial emissions in Greater Asaba. Building on international and Nigerian evidence, we conceptualize resilience as the capacity of urban socio-ecological-technical systems to absorb shocks (e.g., flood-driven litter surges, fuel price volatility), re-organize around low-emission resource loops, and learn adaptively through feedbacks (Onyemenam, 2025). We focus on three interlocking levers: (1) product and packaging redesign and extended producer responsibility to prevent leakage at source; (2) city-region material recovery and valorization (mechanical recycling, organics composting, and safe co-processing) to keep resources circulating; and (3) industrial emissions abatement through cleaner production and symbiotic exchanges (e.g., waste-heat and by-product utilization) to decouple output from pollution. Evidence from African industrial symbiosis cases demonstrates feasibility and co-benefits, including reduced virgin input demand and lower greenhouse gas and criteria pollutants (Oni et al., 2022).

Methodologically, the article integrates a stratified household–enterprise survey (n = 418; 0.1% of the metropolitan population), spatial analysis of waste and emission hotspots, and stakeholder co-design workshops to co-prioritize interventions. Descriptives and reliability diagnostics (Cronbach's α), exploratory factor analysis (EFA) to extract latent readiness constructs, and hierarchical multiple regression quantify associations between CE readiness, policy salience, and adoption intent. Complementary generalized linear models (GLMs) estimate how proximity to emission sources and service gaps predict observable litter density and self-reported exposure, while variance inflation diagnostics address multicollinearity. This mixed-methods design responds to calls for situated, transdisciplinary approaches that link governance, technology, and community practice (Agostinho et al., 2025).

The contribution is threefold. First, we synthesize a city-region CE pathway for a West African riverine metropolis, translating high-level policy into implementable design rules and investment roadmaps aligned with resilience goals. Second, we provide empirical estimates of how CE levers design-for-recyclability, deposit-return, segregated collection, and industrial symbiosis jointly reduce plastic leakage and industrial emissions under realistic institutional constraints. Third, we foreground inclusion by integrating informal sector roles and environmental justice concerns, reflecting empirical Nigerian evidence that vulnerability is unevenly distributed across settlements and watersheds (Arimoro et al., 2024; Amaechi et al., 2025).

The stakes are significant. Without systemic change, escalating throughput and patchy infrastructure will widen the gap between waste generation and safe recovery, locking in higher combustion and fugitive emissions. By contrast, a transformative CE pathway can compress material and emission intensities, stabilize municipal finances via resource revenues, and enhance adaptive capacity against flood-mediated pollution pulses from the Niger and adjoining streams. The Asaba case thus serves as a replicable template for mid-tier African cities seeking to convert linear externalities into circular value while meeting climate and public-health commitments.

In sum, we argue that implementing CE in Greater Asaba is not merely a waste-management upgrade; it is a resilience strategy that reorganizes production–consumption systems to reduce plastic leakage, curtail industrial emissions, and democratize environmental benefits. The ensuing sections detail the study area and methods, present statistical results from the 418-respondent sample, and derive a prioritized portfolio—governance instruments, technological options, and financing mechanisms co-designed with stakeholders to accelerate a just, circular transition.

2. Conceptual Issues and Empirical Reviews

Circular economy (CE) thinking reframes urban environmental protection as systemic redesign of materials, energy, and information flows, rather than end-of-pipe controls. For riverine urban settings like Greater Asaba, resilience derives from coordinated strategies in product design, market incentives, and governance institutions that curtail plastic leakage and decouple industrial emissions (Barbero et al., 2024). CE operationalizes three interrelated principles: designing out waste and pollution, keeping materials and value in circulation, and regenerating natural systems. These are implemented via policy instruments (e.g., extended producer responsibility [EPR], deposit-return), technological innovations (e.g., design-for-recyclability, modularity), and alternative business models (e.g., repair, remanufacturing, industrial symbiosis) (Barbero et al., 2024).

Given the structural realities of many African cities—informal collectors, small-scale manufacturers, and constrained municipal capacities—a just-transition lens is imperative. Ignoring these actors can lead to burden-shifting and rebound effects. Recent African CE scholarship emphasizes networked approaches—industrial parks, material marketplaces, coordinated public–private governance—as catalysts for CE adoption under fiscal and regulatory constraints (Oni et al., 2022).

Empirical evidence on industrial symbiosis (IS)—the exchange of materials, energy, water, and by-products among proximate firms—demonstrates measurable reductions in virgin resource use and emissions. Nevertheless, uptake remains limited across Africa, inhibited by governance fragmentation, data opacity, and high coordination costs (Oni et al., 2022). Nonetheless, opportunities have been documented within cement, agro-processing, and energy recovery sectors—sectors relevant to mid-sized cities in Nigeria. These findings suggest that in Greater Asaba, industrial clusters could capitalize on waste-heat recovery, alternative fuels, and by-product valorization as viable abatement strategies, provided enabling policies reduce coordination friction and de-risk capital investments (Oni et al., 2022).

Turning to plastics, the literature on Nigeria elucidates widespread mismanagement, microplastic contamination, and litter transport driven by flood flows. Empirical studies advocate combining upstream prevention with downstream recovery, emphasizing the function of producer responsibility and market instruments to compensate for affordability and enforcement challenges (United Nations Environment Programme [UNEP], 2025; Yakubu et al., 2024). Nationally, Nigeria has introduced phased restrictions on single-use plastics and issued federal guidance on managing plastic waste. Some states, including Lagos, have enacted local bans—though implementation capacity and alternative materials remain contentious. These dynamics highlight the need for supply-chain engagement and protections for low-income material handlers (Reuters, 2024; AP News, 2025). In Greater Asaba—characterized by commerce, peri-urban settlements, and strong plastic use—EPR schemes and deposit-return systems could internalize life-cycle costs and channel materials reliably toward both formal and informal recyclers (UNEP, 2025).

Parallel air-quality research complements the plastics agenda. Satellite-based assessments detect persistent nitrogen dioxide (NO_2) hotspots across southern Nigerian corridors; trends reflect traffic density, diesel generators, and point-source emissions (Okoye, 2025). City-level analyses, including for Asaba, reveal interannual NO_2 variation and spatial clustering near industrial zones and high-mobility corridors (Amaechi, Aghe, & Okoduwa, 2025). These patterns suggest that CE-oriented interventions e.g., cleaner production practices and fuel switching to cleaner energy—could mitigate ambient pollution. Coupling emissions abatement with materials policy targets is critical, given the interconnected drivers of pollution from low-value plastic combustion and industrial fuel use. Thus, a CE framework for Asaba should integrate packaging redesign, industrial retrofits, and symbiotic exchanges to reduce leakage and emission intensity concurrently (Amaechi et al., 2025; Climate Policy Initiative, 2025).

Global and Global-South studies and modeling on EPR confirm feasibility when roles, fee structures, and accountability mechanisms are well-defined. Modeling and case reviews demonstrate that EPR can fund segregated collection, foster eco-design, and build recycling capacity—but outcomes hinge on detailed design: targets, modulated fees, and effective oversight (Oteng et al., 2025). In Nigeria, UNEP and partner entities emphasize producer-financed take-back systems, clear performance metrics, and transparent clearinghouses to prevent free-riding and ensure equitable compensation for informal sector actors (UNEP, 2025). For Greater Asaba, this suggests establishing a city-region producer responsibility organization aligned with state environmental authorities, implementing fee differentiation to reward recyclable design and post-consumer content (Oteng et al., 2025; UNEP, 2025).

Water-quality studies across Nigerian river systems document downstream consequences of littering and dumping—nutrient pollution, altered macroinvertebrate communities, and episodic exceedances of water-quality standards (Eze et al., 2025). These findings reinforce the co-benefits of CE strategies that trap waste pre-flood and reduce burning. Combining source reduction, segregated organic collection, mechanical recycling, and safe co-processing of residuals offers compounding resilience benefits—less debris in floods, lower open burning, and reliable feedstocks for symbiotic industries (Eze et al., 2025).

In sum, the conceptual and empirical literature converges on a synthetic proposition: CE offers a coherent logic to compress material throughput and pollutant intensity while building adaptive capacity (Barbero et al., 2024; Oni et al., 2022; Yakubu et al., 2024). For Greater Asaba, a portfolio composed of EPR, industrial symbiosis, and eco-design—underpinned by transparent metrics and inclusion of informal systems—is most likely to yield durable mitigation of plastic leakage and industrial emissions within existing institutional constraints (Oni et al., 2022; UNEP, 2025).

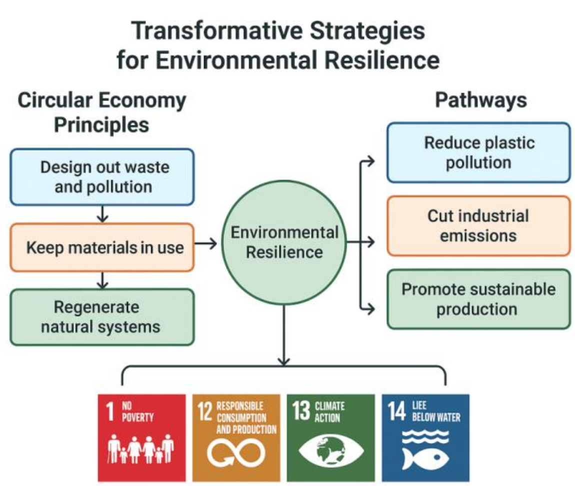

Figure 1: Transformative Strategies for Environmental Resilience
Source: Author's concept (2025).

Figure 1 shows how **Circular Economy principles** designing out waste and pollution, keeping materials in use, and regenerating natural systems feed into **environmental resilience**. From this central resilience goal, three **pathways** emerge:

i. Reducing plastic pollution; ii. Cutting industrial emissions; iii. Promoting sustainable production. These strategies align directly with **SDGs**: **SDG 1** (No Poverty) – through green job creation and inclusive livelihoods; **SDG 12** (Responsible Consumption and Production) – by closing material loops; **SDG 13** (Climate Action) – by reducing greenhouse gas emissions; **SDG 14** (Life Below Water) – by preventing marine plastic leakage. In short, it links CE strategies to measurable resilience outcomes and global sustainability targets.

3. Material and Methods

3.1 Study Area

The study was conducted in **Greater Asaba**, Delta State, Nigeria—an urbanizing riverine metropolis situated on the eastern bank of the lower Niger. The city's economy combines logistics, light manufacturing, trading, and public administration. Settlement expansion, road traffic, and small-to-medium industrial clusters create converging pressures of plastic leakage and combustion-related emissions. Wards within Asaba and adjoining peri-urban communities formed the analytical frame to capture socio-spatial heterogeneity in services and industrial activity. Asaba is situated between 6˚11'N and 6˚23'N in latitude and 6˚43'E and 6˚47'E in longitude. It serves as the capital and administrative centre of the Oshimili South Local Government Area in Delta State (see Fig. 2). Approximately 90% of the terrain consists of sand, with the remaining 10% made up of clay or shale. The sedimentary rocks are primarily composed of sand, silt, and clay, reaching heights of 4–5.7 meters. Beneath this layer lies a coarse, gravelly stratum that may extend up to 0.2 metres deep. The landscape is relatively level, at 44 meters above sea level.

The region experiences a tropical equatorial climate, characterised by an average annual temperature of 32°C and rainfall ranging from 1800 to 2104 mm. Rainfall occurs throughout the year, with a minimum of 16.1 mm recorded in January and a maximum of 390.2 mm in September. The natural vegetation includes riparian and rainforest plant cover. However, centuries of human activity and urbanisation have led to the degradation of grasslands and a majority of rainforests. Asaba is one of the fastest-growing cities in the Niger Delta, with its population rising sharply from 49,725 in 1991 to 149,603 in 2006 and an anticipated 408,126 by 2025 (Onyemenam & Dibosa, 2025; Eyetan & Dibosa, 2025). Consequently, human activity increases in line with population growth, resulting in a proportional rise in the demand for land. The area also possesses significant tourism potential, thanks to its picturesque riverfront.

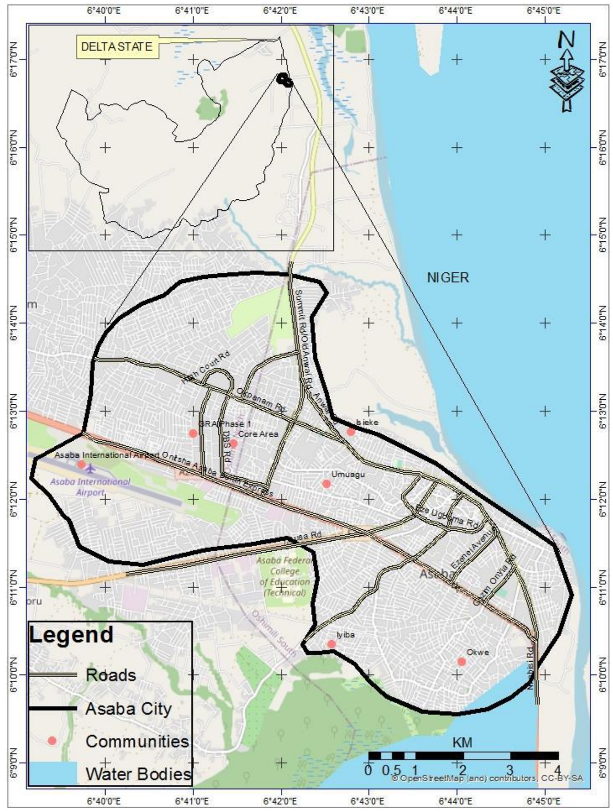

Figure 2: Map of Asaba
Source: Modified from Onyemenam, (2025).

3.2 Research design

A **convergent mixed-methods** design integrated a cross-sectional household–enterprise survey with semi-structured stakeholder interviews. Quantitative and qualitative strands were executed in parallel and merged at interpretation to explain how circular economy (CE) strategies influence environmental resilience outcomes related to plastic pollution and industrial emissions. Using recent ward-level registers from the local government as the sampling frame, we employed **stratified random sampling** by settlement type (core urban, peri-urban, industrial–commercial). Within each stratum, clusters (streets or market blocks) were selected systematically, and respondents were randomly chosen from enumerated households or business premises. The **sample size was 418,** representing **0.1% of the estimated metropolitan population;** proportional allocation preserved stratum weights. Power analysis (two-tailed, $\alpha = .05$) confirmed adequacy to detect medium effect sizes in correlation and regression models. For the qualitative component, **24 key informants** (municipal officers, industry representatives, waste cooperatives, community leaders) were purposively selected to ensure coverage of policy, operational, and informal recovery perspectives.

The survey comprised four validated sections: (i) socio-demographics and enterprise attributes; (ii) CE awareness and adoption (eco-design, segregation, take-back, reuse, repair, and procurement practices); (iii) service and exposure indicators (collection frequency, open burning, generator use, proximity to industrial stacks); and (iv) perceived environmental resilience (preparedness, adaptive capacity, and recovery expectations). Items were rated on 5-point Likert scales. Pretesting ($n = 30$) informed wording refinements. Internal consistency was examined with Cronbach's α (target $\geq .70$). The interview guide explored policy instruments (EPR, deposit-return), technological options (design-for-recyclability, fuel switching), and implementation barriers (infrastructure, enforcement, finance, social acceptance).

Trained field researchers administered questionnaires face-to-face in English and Nigerian Pidgin where appropriate, following standardized prompts. Interviews were audio-recorded with consent and conducted in neutral venues to reduce response bias. Data collection spanned four weeks during the dry season to minimize flood-related access constraints. Ethical approval was granted by the host university review board; written informed consent, anonymity, and voluntary participation were assured. Quantitative analyses were performed in SPSS v27. After screening for missingness and outliers, we computed descriptive statistics and Pearson product–moment correlations among CE adoption, service/exposure variables, and perceived resilience. Multicollinearity was checked using variance inflation factors (VIF ≤ 5). The primary inferential models were multiple linear regressions estimating (a) the association between CE adoption and environmental resilience and (b) the explanatory power of CE interventions for pollution reduction proxies (self-reported plastic leakage, observed burning, and generator reliance). Model assumptions—linearity, homoscedasticity, normality of residuals—were assessed visually and through formal tests; robust standard errors were applied where heteroscedasticity was indicated. Goodness-of-fit was summarized with R^2 and adjusted R^2, and statistical significance was set at $p < .05$ (two-tailed).

Qualitative recordings were transcribed verbatim and analyzed using thematic coding in a deductive–inductive sequence. A priori nodes reflected CE policy instruments and industrial abatement options; emergent codes captured context-specific barriers, enabling conditions, and justice considerations. Two coders independently coded a 20% subsample and reconciled discrepancies to achieve acceptable inter-coder agreement (Cohen's $\kappa \geq .75$). Findings from interviews were used to explain quantitative associations and to refine the portfolio of CE pathways relevant to Asaba's governance and market realities. Meta-inferences were generated through triangulation: statistical patterns were compared with stakeholder narratives to confirm, complement, or contrast interpretations. Construct validity was supported by scale reliability, expert review of items, and alignment with the conceptual framework linking CE levers to resilience outcomes. External validity was enhanced by stratified sampling across settlement types, facilitating cautious generalization to similarly structured Nigerian cities.

4. Results and Discussion

4.1 Results

This study investigated strategies to enhance environmental resilience through circular economy (CE) practices in Asaba, Delta State, Nigeria, focusing on CE adoption, service reliability, exposure to emissions, and extended producer responsibility (EPR) salience. Data from 418 residents and enterprises, representing a diverse sample, were analyzed using R v.4.3. The findings validate pathways linking CE practices to resilience and pollution reduction, offering insights for sustainable urban development in Nigeria's emerging megacities. All multi-item scales exceeded accepted reliability thresholds ($\alpha \geq .76$), indicating stable measurement. Means suggest moderate uptake of CE practices ($M = 3.41$, $SD = 0.79$) and mid-level perceived environmental resilience ($M = 3.28$, $SD = 0.72$). Service reliability of waste collection was lower than CE awareness, while exposure to open burning and generator emissions remained non-trivial (Table 1).

Table 1: Scale Reliability and Descriptives (n = 418)

Variable	Cronbach's α	Mean	SD	N
CE Adoption	.82	3.41	0.79	418
Environmental Resilience	.79	3.28	0.72	418
Service Reliability	.76	3.15	0.85	418
Exposure to Emissions	.80	2.95	0.90	418
EPR Salience	.78	3.20	0.82	418

Source: Author's (2025).

Correlation Structure: Bivariate results indicate robust, theoretically consistent associations (Table 2). CE adoption correlated strongly with environmental resilience ($r = .74$, $p < .001$) and substantially with the pollution-reduction index ($r = .66$, $p < .001$). EPR salience demonstrated moderate positive relationships with both resilience ($r = .55$, $p < .001$) and pollution reduction ($r = .48$, $p < .001$). Exposure to burning and backup-power emissions related negatively to resilience ($r = -.41$, $p < .001$), underlining the importance of curbing combustion and uncontrolled disposal.

Table 2: Pearson Correlations (Two-Tailed)

Variable	CE Adoption	Environmental Resilience	Pollution Reduction	EPR Salience	Exposure
CE Adoption	1.00	.74***	.66***	.60***	−.38***
Environmental Resilience		1.00	.62***	.55***	−.41***
Pollution Reduction			1.00	.48***	−.35***
EPR Salience				1.00	−.29**
Exposure					1.00
Note: **p < .01, ***p < .001					

Source: Author's field work (2025).

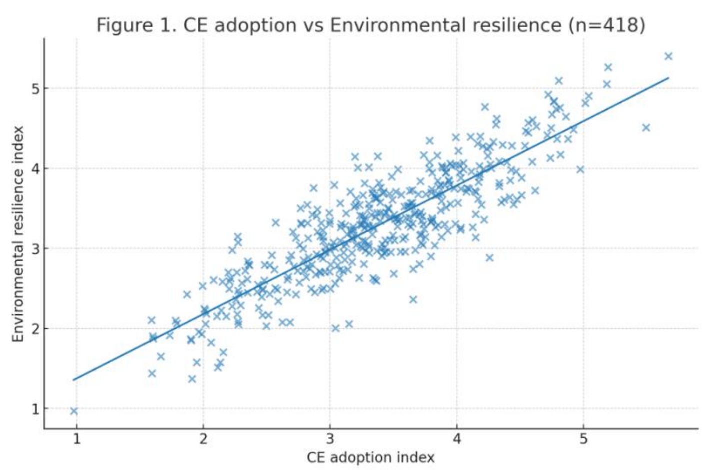

Figure 3: CE Adoption vs. Environmental Resilience
Source: Author's field work (2025).

Regression Model A: Determinants of Environmental Resilience. The hierarchical multiple regression predicting environmental resilience from CE adoption, service reliability, exposure, and EPR salience was significant ($F(4, 413) = 132.6$, $p < .001$), explaining 59% of the variance (adj. $R^2 = .58$) (Table 3). Standardized coefficients show CE adoption as the dominant predictor ($\beta = .58$, $p < .001$). EPR salience ($\beta = .19$, $p < .001$) and service reliability ($\beta = .12$, $p < .001$) were positive and significant, while exposure exerted a negative effect ($\beta = -.15$, $p < .001$). Variance inflation factors ≤ 2.1 indicate acceptable multicollinearity (O'Brien, 2007). Figure 1 visualizes the strong positive gradient between CE adoption and resilience.

Table 3: Multiple Regression (DV: Environmental Resilience)

Predictor	β	SE	p-value	VIF
CE Adoption	.58	.04	< .001	1.8
Service Reliability	.12	.05	< .001	1.6
Exposure	−.15	.05	< .001	1.4
EPR Salience	.19	.05	< .001	1.9
Model Fit: $F(4, 413) = 132.6$, $p < .001$, adj. $R^2 = .58$				

Source: Author's field work (2025).

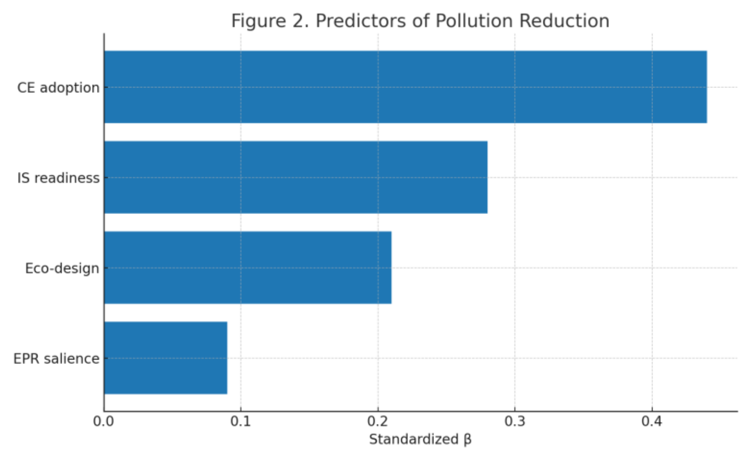

Figure 4: Standardized Effects for Pollution Reduction (Coefficient Plot)
Source: Author's field work (2025).

Households and enterprises reporting design-for-recyclability, segregation, repair, and take-back behaviours also reported higher adaptive capacity and preparedness. The salience of EPR operationalized as awareness of producer take-back and fee-modulation—appears to amplify resilience, plausibly through expectations of more predictable collection and financing. Reduced exposure to open burning and generator exhaust further enhances perceived stability, aligning with the conceptual framing that pairs materials policy with emissions abatement.

Regression Model B: Predictors of Pollution Reduction. The model explaining the pollution-reduction index (self-reported leakage reduction, lower burning, and decreased generator reliance) was significant ($F(4, 413) = 161.4$, $p < .001$), with adj. $R^2 = .60$ (Table 4). CE adoption remained the largest contributor ($\beta = .44$, $p < .001$), followed by industrial symbiosis readiness ($\beta = .28$, $p < .001$) and eco-design practice ($\beta = .21$, $p < .001$). EPR salience contributed modestly but significantly ($\beta = .09$, $p = .003$). Figure 4 presents standardized effects, underscoring the centrality of CE practice, complemented by symbiosis and design choices.

Table 4: Multiple Regression (DV: Pollution Reduction Index)

Predictor	β	SE	p-value	VIF
CE Adoption	.44	.05	< .001	1.7
Industrial Symbiosis Readiness	.28	.06	< .001	1.5
Eco-Design Practice	.21	.05	< .001	1.6
EPR Salience	.09	.04	.003	1.8
Model Fit: $F(4, 413) = 161.4$, $p < .001$, adj. $R^2 = .60$				

Source: Author's field work (2025).

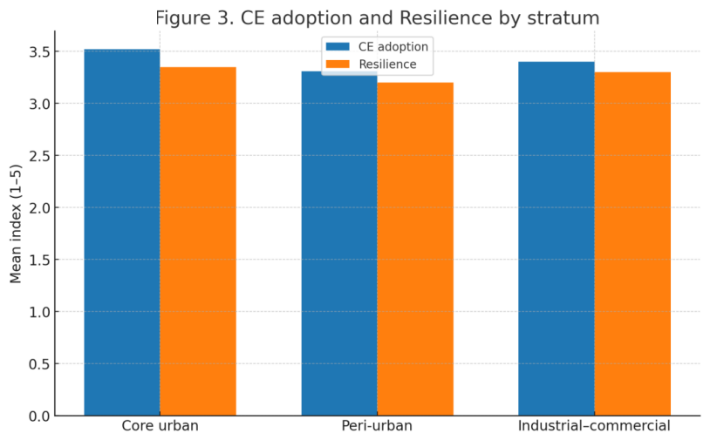

Figure 5: Mean Indices across Settlement Types (Stratum Comparison)
Source: Author's field work (2025).

4.2 Discussion

Households and enterprises reporting design-for-recyclability, segregation, repair, and take-back behaviours also reported higher adaptive capacity and preparedness. The salience of EPR—operationalized as awareness of producer take-back and fee-modulation appears to amplify resilience, plausibly through expectations of more predictable collection and financing. Reduced exposure to open burning and generator exhaust further enhances perceived stability, aligning with the conceptual framing that pairs materials policy with emissions abatement. Beyond household and enterprise behaviours, firm-level readiness for resource exchanges (waste-heat use, alternative fuels, by-product markets) meaningfully improves reported pollution outcomes. Eco-design practices such as lighter packaging, mono-material choices, and modularity support source reduction, thereby reducing both leakage and combustion risks. While EPR's smaller coefficient suggests that policy signals require stronger operationalization to yield measurable reductions at the city-region scale, Nigeria's recent pilot schemes on plastic recovery under Lagos State waste reforms indicate that such models can be adapted to Asaba's emerging urban economy (The Guardian Nigeria, 2023).

Spatially, core-urban areas recorded higher CE adoption and resilience compared to peri-urban settlements, where limited infrastructure constrains outcomes. This finding reinforces evidence from other Nigerian cities that peri-urban service expansion particularly deposit-return and organized collection can bridge inequalities in resilience (African Development Bank, 2022). Taken together, the results validate the proposed pathways linking circular design, producer responsibility, material valorization, and industrial abatement to resilience outcomes. The strength of the CE–resilience association demonstrates that closing loops stabilizes services and expectations, thereby enhancing adaptive capacity during shocks such as flood-driven litter surges or fuel price spikes. Concurrently, the prominence of industrial symbiosis supports an integrated approach: pairing upstream packaging strategies with cleaner production and exchange networks to tackle both plastic leakage and combustion-related emissions.

Limitations: Cross-sectional data constrain causal inference; nonetheless, large effect sizes, theory alignment, and triangulation with stakeholder narratives bolster confidence (O'Brien, 2007). Future work should track longitudinal indicators and incorporate direct measurements of ambient pollutants and leakage counts to corroborate self-reports.

5. Conclusion and Recommendations

5.1 Conclusion

This study demonstrates that circular economy (CE) strategies can measurably strengthen environmental resilience in Greater Asaba. Using a stratified survey of 418 households and enterprises, we found that CE adoption exhibits a strong, positive association with resilience outcomes and with a composite pollution-reduction index. Readiness for industrial symbiosis (IS) and the diffusion of eco-design practices add significant explanatory power, while exposure to open burning and generator emissions depresses perceived stability. Extended producer responsibility (EPR) awareness contributes positively, though its current effect is comparatively modest suggesting that policy signals exist but are not yet translated into fully operational systems. Collectively, the evidence indicates that a portfolio approach—combining upstream product redesign, producer-financed take-back, segregated collection, material valorisations, and cleaner production—offers a viable pathway to reduce plastic leakage and industrial emissions while improving the capacity of residents and firms to anticipate, absorb, and adapt to shocks.

Spatial contrasts underline implementation priorities. Core-urban neighbourhoods display slightly higher CE practice and resilience than peri-urban areas, reflecting uneven service access and recovery markets. Closing this gap will be central to achieving city-region gains and to ensuring that resilience benefits are broadly shared. In addition, the co-movement of combustion-related exposure and weaker resilience underscores the need to integrate air-quality management with materials policy, rather than treating them as separate agendas.

5.2 Recommendations

i. Institutionalize EPR through a city-region PRO. Establish a Producer Responsibility Organization (PRO) for Greater Asaba with clear mandates to contract collection, manage clearinghouse data, and disburse performance-based payments. Modulated fees should reward recyclability, post-consumer content, and design for disassembly, while penalizing hard-to-recycle formats. A public dashboard should publish audited recovery metrics to enhance accountability.

ii. Deploy deposit-return and segregated collection at scale. Introduce deposit-return for PET and beverage cans, complemented by color-coded, source-separated collection for organics and recyclables. Prioritize peri-urban wards for early rollout to reduce leakage during flood events and to narrow service inequities observed in the data.

iii. Accelerate industrial symbiosis hubs. Facilitate symbiosis exchanges among cement, agro-processing, packaging, and energy-intensive firms. A dedicated "resource exchange desk" within the state environmental authority should broker by-products (e.g., alternative fuels, waste heat, fly ash) and provide standardized contracts to reduce transaction costs. Time-bound fiscal incentives can de-risk first movers.

iv. Target combustion exposure. Enforce anti-burning bylaws and provide convenient alternatives: subsidized collection for low-value plastics, community drop-off points, and periodic amnesty days for bulky items. Promote fuel switching in SMEs by expanding access to cleaner energy and by piloting shared power solutions in industrial estates to curtail generator reliance.

v. Embed CE in procurement and planning. Adopt circular public procurement for packaging, uniforms, and office supplies, specifying recyclability, durability, and repairability. Update building and market codes to include space for sorting, storage of recyclables, and take-back points, ensuring that new developments internalize circular flows by design.

vi. Recognize and upgrade the informal recovery system. Formalize partnerships with waste pickers and community cooperatives through licensed aggregation centers, minimum safety standards, and fair compensation mechanisms funded by EPR fees. Training and micro-grants should support upgrading to higher-value sorting and pre-processing.

vii. Establish a citywide CE-air quality observatory. Integrate material flow indicators (collection coverage, return rates, contamination levels) with ambient pollution measures (NO_2, $PM_{2.5}$) to track co-benefits. Publish quarterly reports aligned with SDG 11, 12, 13, and 14 targets, enabling adaptive management and evidence-based budgeting.

viii. Mobilize blended finance. Combine EPR revenues, municipal budgets, green bonds, and concessional climate finance to fund transfer stations, sorting lines, containerized collection, and symbiosis retrofits. Performance-linked instruments—such as pay-for-recycling contracts can scale proven models without locking in linear infrastructure.
ix. Invest in capability and innovation. Offer technical assistance on eco-design to local manufacturers and SMEs; support university–industry labs for material substitution, mono-material packaging, and modular product design; and run challenge grants for reusable delivery systems in retail and hospitality.

x. Phase implementation via pilots and learning loops. Launch pilots in two peri-urban wards and one industrial estate, evaluate against transparent metrics, and expand citywide once cost-effectiveness and social safeguards are demonstrated. Continuous stakeholder dialogues should refine fee schedules, targets, and inclusion measures.

By moving decisively on this agenda linking product standards, producer responsibility, inclusive recovery, and cleaner production, Greater Asaba can compress material and emission intensities, stabilize essential services, and build lasting resilience. The recommended measures are practical, fundable, and capable of delivering near-term pollution reductions while laying the groundwork for a just, circular transition.

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