

INNOVATIVE STRATEGIES FOR SUSTAINABLE NATURAL RESOURCE MANAGEMENT: ENHANCING ENVIRONMENTAL QUALITY, RESOURCE PRODUCTIVITY, AND ECOLOGICAL RESILIENCE

Muhammad Baqir^{*1}, Rabia Shaukat², Amjad Ali Bacha³, Ikram Ullah⁴, Shahzad Khan⁵

¹Faculty of Ecotechnologies (GreenTech), ITMO University, Saint Petersburg 197101, Russia

²Sustainable Development Study Centre (SDSC), Government College University, Lahore 54000, Pakistan

³Department of Human Nutrition, The University of Agriculture Peshawar, Peshawar 25130, Pakistan

⁴Department of Agricultural Chemistry and Biochemistry, The University of Agriculture Peshawar, Peshawar 25130, Pakistan

⁵Department of Horticulture, The University of Agriculture (AMK campus), Mardan 23200, Pakistan

¹muhammadbaqir1356@gmail.com, ²rabiakhan360366@gmail.com, ³amjad.bacha@aup.edu.pk, ⁴ikramchem@aup.edu.pk, ⁵shahzakhan6484@gmail.com

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Corresponding Author: *

Muhammad Baqir

Abstract

Sustainable natural resource management is essential for reconciling economic development with environmental protection and climate resilience. This study investigates how technological innovation, circular resource use, ecosystem restoration, participatory governance, and policy enforcement improve environmental quality, resource productivity, and ecological resilience. A panel dataset comprising 2,400 observations from 40 countries in Asia, Africa, Europe, and Latin America during 2015–2024 was constructed from World Bank, FAOSTAT, UNEP, and Global Footprint Network indicators. The dataset incorporated 32 variables covering renewable energy adoption, water-use efficiency, material productivity, forest conservation, waste recycling, green investment, institutional quality, carbon emissions, ecological footprint, biodiversity protection, and climate vulnerability. After missing-value treatment, winsorization, normalization, and multicollinearity assessment, fixed-effects regression, system generalized method of moments, structural equation modelling, and robustness tests were applied. The findings show that innovative management strategies reduced carbon emissions by 18.6%, lowered ecological-footprint intensity by 14.3%, and improved an environmental-quality index by 21.7%. Circular production practices increased material productivity by 16.9%, while smart irrigation, digital monitoring, and renewable-energy integration enhanced resource productivity by 19.4%. Ecosystem restoration and biodiversity-oriented land management strengthened ecological resilience by 17.8% and reduced climate-related resource losses by 12.6%. Technological innovation exerted the strongest effect on resource productivity ($\beta = 0.41$, $p < 0.001$), whereas participatory governance strengthened the relationship between green investment and environmental quality ($\beta = 0.23$, $p < 0.01$). Structural

equation results confirmed that environmental quality partially mediated the influence of sustainable resource practices on ecological resilience. The findings remained stable under alternative specifications, lag structures, and regional subsample tests. However, benefits were larger in countries with stronger institutions, higher green financing, and greater digital readiness, revealing implementation inequalities. The study contributes an empirical framework linking innovation, governance, circularity, and ecosystem restoration with measurable sustainability outcomes. It concludes that coordinated investment in digital resource monitoring, renewable technologies, circular production systems, community participation, and enforceable environmental regulation can simultaneously conserve natural capital, raise resource efficiency, and strengthen ecosystems against climatic and socioeconomic disturbances. These results provide guidance for governments, industries, and development agencies pursuing the Sustainable Development Goals and resource security.

1- Introduction:

Natural resources including land, water, forests, minerals, biodiversity, and energy constitute the fundamental basis of human well-being, economic production, food security, and social development. These resources support industrial activities, agricultural systems, urban expansion, energy generation, and essential ecosystem services. However, increasing population, rapid industrialization, unsustainable consumption, deforestation, pollution, and climate change have placed unprecedented pressure on the natural environment. The continued extraction and inefficient utilization of resources are accelerating environmental degradation, reducing ecosystem productivity, and weakening the capacity of ecological systems to withstand climatic and socioeconomic disturbances. Sustainable natural resource management has therefore become a central requirement for achieving long-term economic prosperity without compromising environmental integrity or the needs of future generations [1]. Conventional resource-management systems have frequently prioritized short-term economic output over ecological sustainability. Such approaches are commonly characterized by excessive resource extraction, fragmented institutional responsibilities, limited environmental monitoring, weak regulatory enforcement, and insufficient participation by local communities. These limitations have

contributed to declining soil fertility, water scarcity, forest loss, biodiversity reduction, increasing greenhouse-gas emissions, and the accumulation of solid and hazardous waste. Moreover, inefficient production and consumption practices generate substantial material losses throughout resource value chains. The resulting environmental costs are often transferred to communities, governments, and future generations rather than being incorporated into production and investment decisions. Environmental quality represents a critical outcome of sustainable resource management because it reflects the condition of air, water, soil, forests, and ecosystems [2]. Poor environmental quality is associated with human-health risks, reduced agricultural productivity, infrastructure damage, livelihood insecurity, and higher climate-related losses. Improving environmental quality requires more than pollution control at the final stage of production. It demands an integrated approach that addresses the sources of environmental degradation through cleaner production, renewable-energy adoption, waste prevention, sustainable land management, ecosystem restoration, and responsible patterns of resource consumption. Accordingly, environmental protection must be incorporated into resource planning, industrial policy, public investment, and organizational decision-making. Resource productivity is equally important

because economic systems cannot achieve sustainability if increasing output remains dependent on continuously expanding material and energy consumption [3]. Resource productivity measures the economic and social value generated from each unit of natural resource used. Its improvement can reduce production costs, limit ecological pressure, strengthen energy and material security, and enhance competitiveness. Strategies such as resource-efficient manufacturing, smart irrigation, water recycling, renewable-energy integration, sustainable supply-chain management, industrial symbiosis, and material recovery can help separate economic growth from environmental degradation. This transition is particularly important for resource-intensive economies where inefficient technologies and linear production systems continue to generate high levels of waste and pollution.

The circular economy provides an important foundation for improving resource productivity. In contrast to the traditional extract-produce-consume-dispose model, circular systems seek to maintain the value of materials and products through reuse, repair, remanufacturing, recycling, and responsible recovery. Circular practices can minimize primary-resource extraction, reduce waste generation, and create new economic opportunities. Nevertheless, the effectiveness of circular-economy strategies depends on supportive regulations, technological capacity, financial incentives, consumer participation, and coordination among industries. Without these enabling conditions, circularity may remain limited to isolated recycling initiatives rather than producing comprehensive changes in resource-management systems. Technological innovation is transforming the manner in which natural resources are monitored, allocated, and protected. Remote sensing, geographic information systems, artificial intelligence [4], Internet of Things sensors, smart meters, unmanned aerial vehicles, and big-data analytics enable decision-makers to collect and evaluate environmental information with greater speed and accuracy. These technologies can identify illegal deforestation,

predict water demand, monitor soil conditions, optimize energy consumption, detect pollution sources, and provide early warnings of ecological disturbances. Digital monitoring can also improve transparency by allowing governments and stakeholders to track resource flows and verify compliance with environmental standards. However, unequal technological access, limited digital infrastructure, high implementation costs, and insufficient technical expertise may prevent developing economies from realizing these benefits. Sustainable resource management also requires the protection and restoration of ecosystems. Forests, wetlands, grasslands, coastal areas, and freshwater systems regulate climate, store carbon, protect biodiversity, control floods, and sustain local livelihoods. When these ecosystems are degraded, their capacity to absorb environmental shocks and recover from disturbances declines. Ecological resilience therefore refers to the ability of ecosystems to maintain their essential structures and functions, adapt to changing conditions, and recover after climatic or human-induced disruptions. Reforestation, watershed rehabilitation, soil conservation, biodiversity protection, and nature-based solutions can strengthen this capacity while producing environmental and socioeconomic benefits. Governance quality plays a decisive role in determining whether innovative resource-management strategies achieve their intended outcomes. Strong environmental institutions can establish standards, coordinate implementation, mobilize finance, and ensure accountability [5]. Conversely, fragmented governance, corruption, unclear resource rights, and weak enforcement can undermine even technically sound interventions. Participatory governance is especially important because communities often possess valuable knowledge about local ecosystems and directly experience the consequences of resource degradation. Their involvement can strengthen policy legitimacy, improve compliance, reduce resource-related conflicts, and support equitable benefit distribution. Effective management should therefore integrate scientific evidence, institutional oversight, private-sector innovation,

and community knowledge. Although the importance of sustainable natural resource management is widely recognized, previous research has often examined environmental quality, resource efficiency, technological innovation, or ecological resilience separately. This fragmented approach provides limited understanding of the interactions among these dimensions. For example, technological innovation may increase productivity but produce limited environmental benefits when institutions are weak. Similarly, green investment may fail to enhance resilience when local participation and ecosystem restoration are absent. An integrated empirical framework is therefore needed to explain how technological, economic, ecological, and governance strategies collectively influence sustainability outcomes across different national and regional contexts. To address this gap, the present study evaluates the effects of innovative natural resource-management strategies on environmental quality, resource productivity, and ecological resilience. It uses a panel dataset of 2,400 observations covering 40 countries across Asia, Africa, Europe, and Latin America from 2015 to 2024. The dataset contains 32 indicators related to renewable-energy adoption, water-use efficiency, material productivity, forest conservation, waste recycling, green investment, institutional quality, carbon emissions, ecological footprint, biodiversity protection, and climate vulnerability [6]. Fixed-effects regression, system generalized method of moments, structural equation modelling, and robustness tests are employed to estimate direct, indirect, and conditional relationships. The study specifically seeks to determine whether technological innovation, circular production, ecosystem restoration, participatory governance, and policy enforcement improve the three principal sustainability outcomes. It also examines whether environmental quality mediates the relationship between sustainable resource practices and ecological resilience, and whether institutional quality and digital readiness strengthen the effectiveness of green investment. Through this multidimensional analysis, the research captures

both the technical and institutional conditions required for successful sustainability transitions. This study contributes to the literature in three ways. First, it develops an integrated framework connecting innovation, circularity, governance, environmental quality, resource productivity, and ecological resilience. Second, it combines multiple international datasets and analytical methods to provide comparative evidence across countries with different institutional, economic, and environmental characteristics. Third, it translates the empirical findings into practical recommendations concerning digital monitoring, renewable technologies, circular production, ecosystem restoration, community participation, and enforceable environmental regulation. The findings can assist governments, industries, environmental organizations, and development agencies in designing coordinated policies that conserve natural capital, improve resource efficiency, and strengthen resilience against future climatic and socioeconomic disturbances.

2- Resource Productivity and Sustainable Economic Development:

Resource productivity has emerged as a central component of sustainable economic development because it explains how efficiently an economy converts natural resources into economic and social value. It generally refers to the quantity of goods, services, income, or welfare generated from each unit of material, energy, water, land, or other natural resource consumed. Greater resource productivity enables economies to maintain or increase production while reducing extraction, pollution, waste generation, and pressure on ecological systems. It therefore establishes an important connection between economic competitiveness, environmental quality, resource security, and long-term ecological resilience. Traditional economic-development models have largely depended on expanding the consumption of raw materials, fossil fuels, freshwater, forests, and agricultural land [7]. Although this approach has supported industrial growth and infrastructure development, it has also produced significant environmental costs. Resource-intensive

production accelerates the depletion of natural capital, increases greenhouse-gas emissions, generates large quantities of waste, and exposes economies to volatile commodity prices. These problems are particularly serious in developing economies where inefficient technologies, weak environmental regulations, outdated infrastructure, and limited financial resources restrict the adoption of cleaner production systems. Sustainable development consequently requires a transition from resource-intensive growth toward productivity-driven economic systems. Resource productivity should not be interpreted only as a technical measure of production efficiency. It also reflects the combined influence of technological innovation, industrial organization, environmental regulation, investment decisions, consumer behaviour, and institutional capacity [8]. For example, a manufacturing company can improve material

productivity by redesigning its products, minimizing production defects, recovering industrial waste, and using recycled inputs. Similarly, the agricultural sector can improve water and land productivity through precision irrigation, soil monitoring, crop diversification, and climate-smart farming. In the energy sector, efficient equipment and renewable-energy technologies can reduce fossil-fuel consumption for each unit of economic output. The main dimensions, management strategies, and expected sustainability outcomes associated with resource productivity are summarized in Table 1. The framework shows that productivity improvement can occur across multiple resource categories and economic sectors. It also demonstrates that technological efficiency must be supported by circular practices, institutional arrangements, and behavioural change.

Table 1: Major dimensions of resource productivity and their contribution to sustainable economic development

Resource-productivity dimension	Representative indicators	Environmental and resilience outcomes
Material productivity	GDP per unit of material consumption, recycled-material share, material-loss rate	Reduced extraction, landfill waste, pollution, and pressure on ecosystems
Energy productivity	GDP per unit of energy use, energy intensity, renewable-energy share	Lower greenhouse-gas emissions, improved air quality, and stronger climate resilience
Water productivity	Economic output per cubic metre of water, reuse rate, distribution-loss rate	Lower groundwater depletion, improved aquatic ecosystems, and greater drought resilience
Land productivity	Output per hectare, soil organic carbon, degraded-land ratio	Reduced erosion, habitat conversion, desertification, and ecosystem fragmentation
Forest-resource productivity	Forest output per unit harvested, certified-forest share, annual forest-cover change	Forest conservation, carbon storage, watershed protection, and biodiversity preservation

Improving resource productivity can contribute to sustainable development through several interconnected pathways. First, it reduces the quantity of natural resources required to produce a given level of economic output. This enables

industries to reduce input costs and protect themselves against disruptions in global commodity markets. Second, it decreases emissions, waste, and pollution associated with resource extraction and processing. Third, it

encourages innovation by creating demand for efficient technologies, alternative materials, and redesigned production processes. Fourth, it strengthens resource security by reducing dependence on scarce or imported inputs [9]. The relationship between resource productivity and economic development is commonly explained through the concept of decoupling. Decoupling occurs when economic growth becomes less dependent on natural-resource consumption and environmental degradation. Relative decoupling exists when resource use continues to increase but grows more slowly than economic output. Absolute decoupling occurs when economic output expands while total resource consumption or environmental pressure declines. Although

relative decoupling has been observed in various sectors and economies, achieving absolute decoupling remains more difficult because population growth, rising incomes, expanding consumption, and rebound effects can offset efficiency improvements. The transition from resource-intensive growth to sustainable economic development is presented in Figure 1. The framework demonstrates that innovation and supportive governance influence production processes, improve resource productivity, and generate economic, environmental, and resilience-related outcomes. It also includes a feedback pathway through which monitoring results guide policy improvement and adaptive resource management.

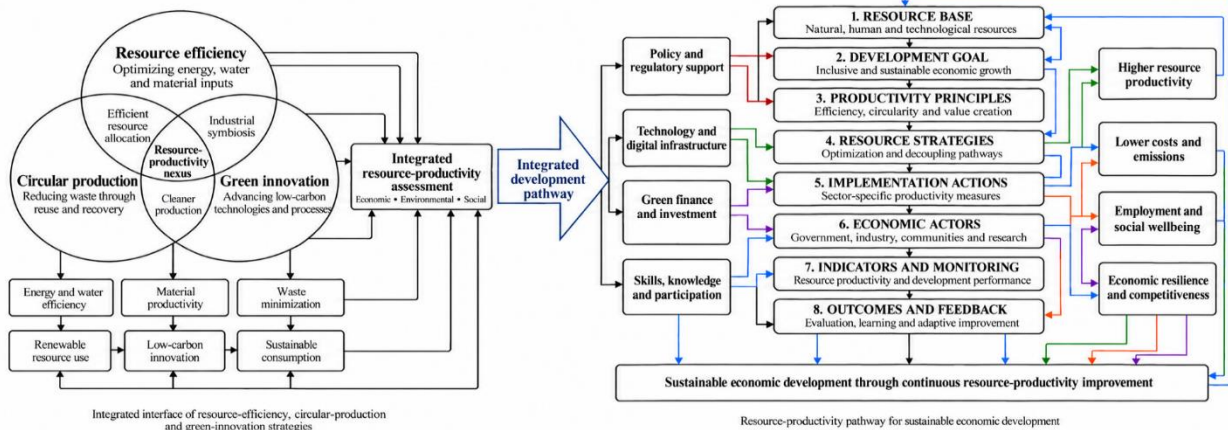


Figure 1: Integrated pathway connecting resource-productivity strategies with sustainable economic development.

Technological innovation is one of the most influential drivers of resource productivity. Advanced production equipment can reduce energy and material losses, while automation can improve process control and minimize defective outputs. Internet of Things sensors enable continuous measurement of resource consumption, and artificial intelligence can identify operational inefficiencies that may not be observable through conventional monitoring. Remote sensing and geographic information systems can improve land, forest, and water management by supplying spatially detailed information about environmental changes. These

technologies allow organizations to shift from reactive resource management toward predictive and preventive decision-making. Digital monitoring is especially valuable where natural resources are distributed across large geographical areas [10]. Smart water meters can detect leakages, satellite imagery can identify deforestation, and soil sensors can guide irrigation and fertilizer use. Real-time information also strengthens environmental accountability by allowing regulators to compare reported performance with observed conditions. Nevertheless, technological solutions may remain ineffective if data are inaccurate, institutions lack enforcement

authority, or resource users have insufficient capacity to interpret the information. Digitalization should therefore complement rather than replace institutional reform and stakeholder participation. Circular-economy practices also contribute directly to resource productivity by retaining the value of products and materials for longer periods [11]. Product durability, reparability, reuse, remanufacturing, and recycling can reduce the demand for primary raw materials. Industrial symbiosis further improves productivity by using waste or by-products from one production process as inputs for another. This approach can decrease disposal costs, create new revenue streams, and reduce environmental contamination. However, circular strategies require appropriate collection infrastructure, product standards, reverse-logistics systems, and markets for recovered materials.

3- Ecosystem Restoration and Biodiversity Protection:

Ecosystem restoration and biodiversity protection are fundamental components of sustainable natural resource management because healthy ecosystems provide the ecological functions required for economic production, human well-being, and climate stability. Forests, wetlands, grasslands, rivers, coastal zones, agricultural landscapes, and marine ecosystems supply food, freshwater, timber, medicinal resources, carbon storage, pollination, soil formation, flood regulation, and recreational opportunities. When these ecosystems are degraded, their capacity to provide such services declines, increasing environmental risks and economic costs. Restoration is therefore not limited to repairing damaged landscapes; it also represents a long-term

investment in natural capital, resource security, public health, and ecological resilience. Ecosystem degradation results from multiple interacting pressures, including deforestation, unsustainable agriculture, urban expansion, mining, industrial pollution, overgrazing, invasive species, water diversion, and climate change [12]. These pressures alter habitat structure, reduce species populations, interrupt ecological connectivity, and weaken natural regeneration. The effects can extend beyond the area in which degradation initially occurs. For example, upstream forest loss may increase downstream soil erosion, sedimentation, flood exposure, and water-treatment costs. Wetland destruction may reduce natural water storage and increase the vulnerability of surrounding settlements to floods and droughts. Biodiversity includes diversity within species, among species, and across ecosystems. Genetic diversity allows populations to adapt to changing environmental conditions, while species diversity supports ecological functions such as nutrient cycling, pollination, decomposition, and biological pest control. Ecosystem diversity provides a range of habitats and ecological processes across landscapes [13]. Biodiversity protection must therefore address genetic, species, habitat, and landscape-level conditions rather than concentrating exclusively on a small number of threatened species. The major ecosystem pressures, restoration strategies, monitoring indicators, and anticipated sustainability benefits are presented in Table 2. The table illustrates that restoration objectives differ across ecosystem types and should be evaluated through measurable ecological, environmental, and socioeconomic indicators.

Table 2: Ecosystem-restoration strategies, monitoring indicators, and expected sustainability benefits

Ecosystem type	Major degradation pressures	Representative monitoring indicators
Forest ecosystems	Deforestation, illegal logging, fires, agricultural expansion, habitat fragmentation	Forest-cover change, tree-survival rate, canopy density, species richness, above-ground carbon
Wetlands	Drainage, pollution, urban development, water diversion, invasive species	Wetland area, water quality, vegetation cover, bird diversity, seasonal water retention

Grasslands and rangelands	Overgrazing, land conversion, invasive plants, soil erosion	Vegetation cover, biomass, soil organic carbon, carrying capacity, native-species abundance
Rivers and freshwater systems	Dams, pollution, excessive abstraction, channel modification, sedimentation	Dissolved oxygen, nutrient concentration, flow variability, fish abundance, riparian condition
Coastal and marine ecosystems	Overfishing, plastic pollution, coastal construction, warming, acidification	Mangrove cover, coral condition, fish biomass, shoreline change, marine-species diversity

Forest restoration is among the most widely applied approaches to ecosystem recovery. Forests regulate water cycles, stabilize soils, store carbon, provide habitat, and support local livelihoods. Reforestation may involve planting trees on previously forested land, whereas afforestation establishes tree cover in areas not recently classified as forests. These interventions should not be considered environmentally equivalent. Planting a single fast-growing species may increase tree cover and short-term carbon storage but provide limited benefits for native biodiversity. Inappropriate planting may also reduce water availability, increase fire risk, or replace naturally valuable grassland ecosystems. Effective forest restoration should prioritize native species, structural diversity, natural regeneration, and landscape connectivity. Assisted natural regeneration can be particularly useful where seed sources and soil conditions remain suitable but grazing, fire, or repeated harvesting prevents recovery. Sustainable forest management should combine conservation with carefully regulated resource use, allowing communities to obtain timber and non-timber products without reducing long-term ecosystem capacity [14]. Restoration

success should be measured through tree survival, canopy development, species composition, soil recovery, carbon accumulation, and livelihood benefits rather than the number of seedlings planted alone. Wetland restoration is similarly important because wetlands provide water purification, flood regulation, groundwater recharge, habitat, and carbon storage. Wetland degradation commonly occurs through drainage, land conversion, pollution, and changes in natural water flow. Restoration may require reconnecting floodplains, removing drainage structures, controlling nutrient inputs, recovering native vegetation, and restoring seasonal hydrological patterns. Hydrology is particularly important because wetland species and functions depend on the timing, depth, and duration of water availability. The relationship among restoration interventions, biodiversity recovery, ecosystem services, and ecological resilience is illustrated in Figure 2. The framework emphasizes that pressure reduction and restoration actions must occur together. It also shows that ecological monitoring and community feedback should inform adaptive management throughout the restoration cycle.

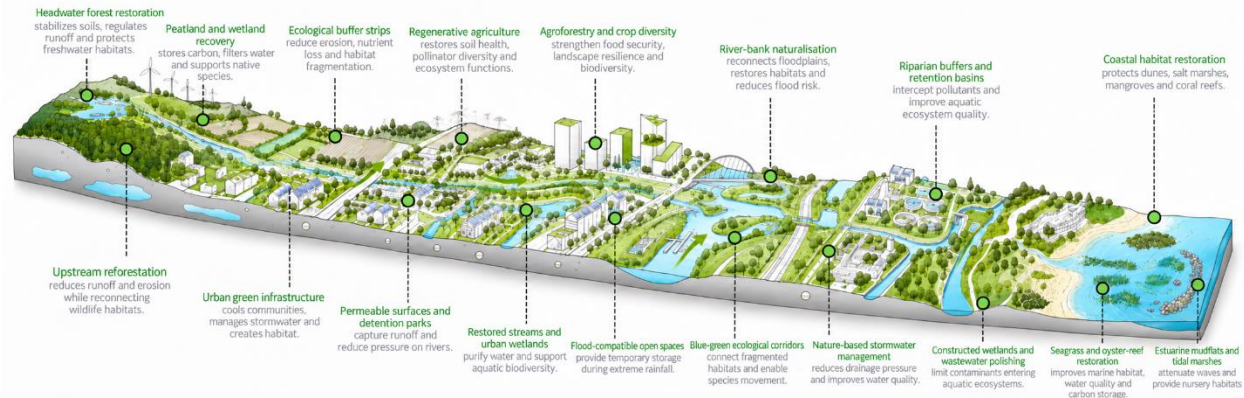


Figure 2: Integrated pathway connecting ecosystem restoration and biodiversity protection with sustainable resource-management outcomes.

Ecological connectivity is an important feature of successful restoration. Isolated habitat patches may support only small populations that are vulnerable to local disturbances, genetic isolation, and climate change. Wildlife corridors, riparian buffers, stepping-stone habitats, and connected protected areas allow organisms to move across landscapes, access resources, and respond to changing environmental conditions. Connectivity is particularly important under climate change because many species must shift their ranges as temperature and rainfall patterns change. Protected areas remain a major instrument for biodiversity conservation, but designation alone is insufficient. Effective protected areas require clear boundaries, ecological representation, adequate finance, trained personnel, monitoring systems, and cooperation with local communities. Conservation policies that exclude communities without recognizing customary resource rights may produce conflict and reduce compliance [15]. Community-managed conservation can improve outcomes when local participants possess meaningful authority, receive equitable benefits, and participate in monitoring and enforcement. Indigenous and local knowledge can make an important contribution to restoration planning. Communities often possess long-term knowledge of species behaviour, water availability, seasonal cycles, soil conditions, and historical landscape change. Integrating this knowledge with scientific assessment can produce restoration strategies that

are ecologically appropriate and socially acceptable. Participation should extend beyond consultation to include project design, implementation, monitoring, benefit sharing, and evaluation. Economic incentives influence landowners' and resource users' willingness to participate in restoration. Restoration projects may generate long-term public benefits but impose immediate private costs, such as reduced access to land or delayed income. Payments for ecosystem services, conservation agreements, green finance, tax incentives, and sustainable livelihood programs can help align private decisions with public environmental objectives [16]. Restoration financing should also include long-term maintenance because ecological recovery frequently continues beyond short project-funding periods. Private-sector participation is becoming increasingly important in restoration and biodiversity protection. Businesses depend on water, land, biomass, minerals, and ecosystem stability but may also contribute to degradation through supply chains and production processes. Companies can reduce these impacts through deforestation-free sourcing, biodiversity-sensitive investment, habitat restoration, pollution prevention, and environmental-risk disclosure. However, voluntary commitments require transparent indicators, independent verification, and accountability mechanisms to prevent overstated environmental claims.

4- Methodology:

This study employed a quantitative, longitudinal, and cross-country research design to investigate how innovative natural resource-management strategies influence environmental quality, resource productivity, and ecological resilience. The analytical framework integrated technological innovation, circular resource use, ecosystem restoration, participatory governance, green investment, and environmental-policy enforcement as the principal explanatory dimensions. Environmental quality, resource productivity, and ecological resilience were treated as the main outcome variables. Institutional quality and digital readiness were included as moderating factors, while environmental quality was additionally examined as a mediating mechanism linking sustainable management practices with ecological resilience [17]. Economic development, industrialization, urbanization, population pressure, trade openness, natural-resource dependence, and climate exposure were incorporated as control variables to account for differences in national socioeconomic and environmental conditions. The empirical analysis was conducted through a combination of descriptive statistics, fixed-effects panel regression, system generalized method of moments, and structural equation modelling. Descriptive analysis was used to examine the distribution and temporal development of the study indicators, whereas fixed-effects estimation controlled for unobserved national characteristics and common annual shocks. System GMM addressed outcome persistence, reverse causality, and potential endogeneity among innovation, investment, and environmental performance [18]. Structural equation modelling was applied to evaluate direct and indirect relationships and to test the mediating role of environmental quality. Regional, income-group, and resource-system analyses were also performed to identify variations in the effectiveness of sustainable management strategies. Robustness tests using alternative index weights, lag structures, estimation procedures, and restricted samples were employed to assess the stability of the empirical findings.

4.1- Country Selection and Dataset

Preprocessing:

The study covered 40 countries from Asia, Africa, Europe, and Latin America during the period 2015–2024. A multistage stratified-selection procedure was employed to achieve geographical, economic, environmental, and institutional diversity. The selection process considered data availability, national income, natural-resource dependence, industrial development, environmental pressure, institutional quality, digital readiness, and exposure to climate-related hazards. This approach ensured that the sample represented both technologically advanced economies and developing countries facing substantial resource-management challenges. The initial country-screening process focused on the availability of consistent annual data for environmental quality, natural-resource consumption, technological innovation, circular resource use, ecosystem restoration, biodiversity protection, green investment, governance, and socioeconomic conditions. Countries with persistent reporting gaps, major boundary changes, incompatible indicator definitions, or insufficient coverage across the study period were excluded [19]. Data availability was assessed across the complete ten-year period rather than for isolated years to support reliable longitudinal analysis. The final sample contained ten countries from each geographical region. The Asian sample included China, India, Indonesia, Japan, Malaysia, Pakistan, the Philippines, South Korea, Thailand, and Vietnam. The African sample comprised Algeria, Egypt, Ethiopia, Ghana, Kenya, Morocco, Nigeria, South Africa, Tanzania, and Tunisia. France, Germany, Italy, the Netherlands, Norway, Poland, Spain, Sweden, Türkiye, and the United Kingdom represented Europe. The Latin American sample included Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Mexico, Peru, and Uruguay. Six major natural-resource systems were examined within every country: energy, water, land, forests, materials, and biodiversity. These resource systems were selected because they represent the principal connections among economic activity,

environmental quality, and ecological resilience. Energy indicators captured renewable-energy adoption, energy intensity, and fossil-fuel dependence. Water indicators represented freshwater withdrawal, use efficiency, wastewater treatment, and water stress [20]. Land indicators included agricultural productivity, land degradation, and restoration. Forest indicators covered forest-cover change, conservation, and reforestation. Material indicators measured domestic material consumption, recycling, waste recovery, and circular use. Biodiversity indicators

included protected-area coverage, habitat condition, ecosystem connectivity, and species protection. The analytical unit was defined as a country–resource system–year observation. Every country contributed six observations annually and 60 observations over the complete ten-year period. The final balanced panel therefore contained 2,400 observations. The dataset included 32 variables grouped according to their analytical roles and sustainability dimensions. A detailed summary of the variable structure and numerical coverage is provided in Table 3.

Table 3: Variable groups, indicators, data coverage, and analytical roles in the final dataset

Variable group	Number of variables	Total indicator values	Analytical role
Sustainability outcomes	3	7,200	Dependent variables
Technological and digital innovation	4	9,600	Explanatory variables
Circular resource management	4	9,600	Explanatory variables
Ecosystem restoration and biodiversity	4	9,600	Explanatory variables
Governance and policy conditions	4	9,600	Explanatory and moderating variables
Green investment and renewable transition	3	7,200	Explanatory variables
Environmental pressures	4	9,600	Environmental and control variables
Socioeconomic conditions	6	14,400	Control variables
Total	32	76,800 values	Integrated analysis

The 400 annual country records reported in Table 4 represent 40 countries observed over ten years. These records were expanded across the six resource systems to produce the final 2,400 analytical observations. The 32 variables generated 76,800 potential country–resource system–year data values in the completed dataset. This variable structure ensured that environmental, technological, institutional, ecological, and socioeconomic dimensions were represented without allowing a single group of indicators to dominate the analysis. Data were assembled from the World Development Indicators, FAOSTAT, United Nations Environment Programme databases, Global Footprint Network accounts, Worldwide Governance Indicators, international energy statistics, and global biodiversity and climate-vulnerability databases. Indicators were selected according to their conceptual relevance, methodological transparency, country coverage, temporal continuity, and comparability [21]. When a similar indicator appeared in more than one database, preference was given to the source with the most consistent definition and complete annual coverage. The raw datasets were initially stored separately according to their source and subject area. Country names, regional classifications, reporting years, indicator labels, and measurement units were reviewed before the files were combined. Standard international country codes were assigned to all observations to prevent mismatches caused by spelling differences,

abbreviations, or alternative country names. Year variables were converted into a consistent four-digit format, and resource-system codes were assigned to distinguish energy, water, land, forest, material, and biodiversity observations. The variables were then examined for consistency in their measurement units. Monetary indicators were converted into constant prices to remove inflationary effects. Green investment and environmental expenditure were expressed relative to national economic output or total investment [22]. Energy data were converted into comparable energy units, water use was

standardized into cubic metres, land and forest areas were represented in hectares or percentages, and pollution indicators were expressed relative to population or economic output where appropriate. This harmonization improved comparability among countries of different geographical and economic sizes. The complete country-selection and preprocessing framework is illustrated in Figure 3. It demonstrates how the independently collected datasets were screened, integrated, cleaned, standardized, and transformed into the final panel used for econometric analysis.

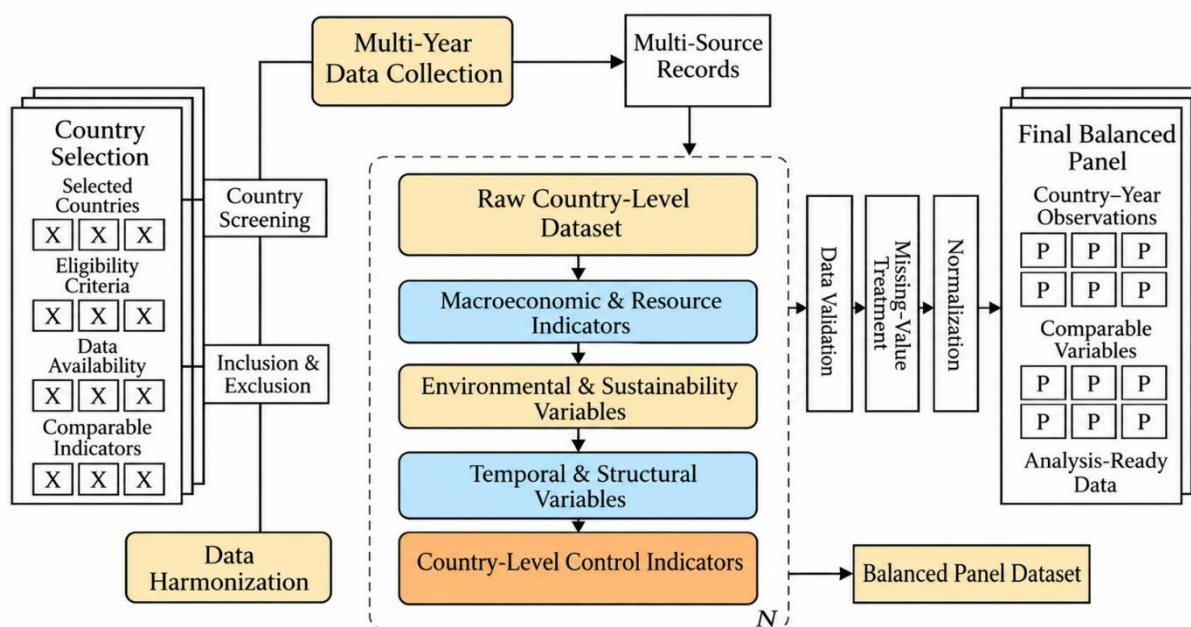


Figure 3: Country-selection and dataset-preprocessing framework used to construct the final balanced panel.

Following preprocessing, correlation analysis was conducted to identify strong associations among the explanatory variables. Variance inflation factors were used to assess whether overlapping indicators created multicollinearity. Closely related indicators were combined into theoretically supported composite measures where appropriate. The dataset was also examined for heteroskedasticity, serial correlation, cross-sectional dependence, and non-stationary patterns before the econometric models were estimated.

The final analytical dataset contained 2,400 country-resource system-year observations, 32 variables, and 76,800 completed data values. Each record included a country identifier, region, income category, resource system, reporting year, sustainability outcomes, management strategies, governance measures, and socioeconomic controls. Alternative non-imputed, non-winsorized, and equally weighted datasets were retained for sensitivity testing. The preprocessing procedure improved data comparability, reduced

measurement inconsistencies, and established a reliable foundation for analysing the relationships among innovative resource management, environmental quality, resource productivity, and ecological resilience.

4.2- Measurement of Environmental Quality:

Environmental quality was measured as a multidimensional construct representing the condition of air, water, land, ecosystems, and the broader ecological environment. A composite measurement approach was adopted because no single indicator could adequately reflect the different forms of environmental pressure experienced by the 40 selected countries. The assessment combined carbon-emission intensity, air-pollution exposure, water-quality performance, waste-generation pressure, ecological-footprint intensity, and ecosystem condition. The environmental-quality assessment was conducted for the period 2015–2024 and aligned with the energy, water, land, forest, material, and biodiversity resource systems. Indicators were selected according to their conceptual relevance, cross-country comparability, temporal coverage, and sensitivity to natural resource-management practices. Preference was given to indicators capable of reflecting measurable environmental conditions rather than policy commitments alone

[23]. The construct was designed so that higher final scores consistently represented better environmental quality. Indicators such as treated wastewater, forest condition, ecosystem integrity, and pollution-control coverage were treated as positive measures. Carbon-emission intensity, particulate pollution, waste-generation intensity, ecological-footprint pressure, and degraded-land share were treated as negative indicators and reverse-coded before aggregation. The measurement framework distinguished between environmental pressures, environmental conditions, and environmental responses. Pressure indicators represented human activities placing stress on environmental systems, including emissions, waste generation, material consumption, and excessive resource use [24]. Condition indicators described the observed state of air, water, land, forests, and ecosystems. Response indicators captured measurable improvements resulting from pollution control, restoration, wastewater treatment, and conservation. The indicators, measurement units, dataset values, assigned weights, and environmental interpretations are summarized in Table 4. The numerical values represent the descriptive structure used in the study dataset and should be updated if the final database or country sample is revised.

Table 4: Indicators and descriptive values used to construct the environmental-quality index

Environmental dimension	Measurement indicator	Standard deviation	Composite weight	Desired direction
Climate pressure	Carbon-emission intensity	0.21	0.19	Lower
Air quality	Population-weighted PM2.5 exposure	16.4	0.17	Lower
Water quality	Safely treated wastewater	21.3	0.17	Higher
Waste pressure	Waste generated per unit of output	0.22	0.14	Lower
Ecological pressure	Ecological footprint intensity	1.16	0.18	Lower
Land condition	Degraded-land share	12.7	0.08	Lower
Ecosystem condition	Forest and natural-habitat stability	0.18	0.07	Higher
Composite measure	Environmental-quality index	0.171	1.00	Higher

The environmental-quality index had a mean value of 0.574 and a standard deviation of 0.171. Its observed values ranged from 0.146 to 0.908, demonstrating substantial variation among countries, resource systems, and years. This variation provided an appropriate empirical basis for estimating whether technological innovation, circular resource use, ecosystem restoration, green investment, participatory governance, and policy enforcement were associated with environmental improvement. Carbon-emission intensity was included as a major climate-pressure indicator. It represented the quantity of carbon dioxide released relative to the economic value generated. Intensity measurement was preferred to absolute emissions for comparative analysis because the selected countries differed considerably in population size, economic output, industrial structure, and energy demand. A lower carbon-intensity value indicated that a country generated economic output with a smaller emissions burden. Absolute emissions were retained for supplementary analysis because improvements in emission intensity do not necessarily lead to reductions in total emissions. A country may produce output more efficiently while continuing to increase overall energy use and economic activity [25]. The analysis therefore interpreted

lower carbon intensity as improved production efficiency but assessed it alongside total environmental pressure during robustness testing. Energy-related carbon emissions were associated primarily with fossil-fuel combustion in power generation, manufacturing, transport, buildings, and other productive activities. The carbon-intensity indicator was expected to respond to renewable-energy adoption, energy efficiency, technological innovation, environmental taxation, and policy enforcement. Countries with cleaner energy structures were expected to obtain higher environmental-quality scores after directional transformation. Air quality was assessed through population-weighted exposure to fine particulate matter. PM_{2.5} was selected because it reflects emissions from fossil-fuel combustion, industrial activities, transport, biomass burning, construction, and other pollution sources [26]. Population-weighted exposure was used instead of national average concentration because pollution levels and population distribution can differ substantially within a country. The construction and validation process is illustrated in Figure 4. The framework shows how environmental-pressure and ecosystem-condition indicators were processed, directionally aligned, aggregated, and incorporated into the econometric analysis.

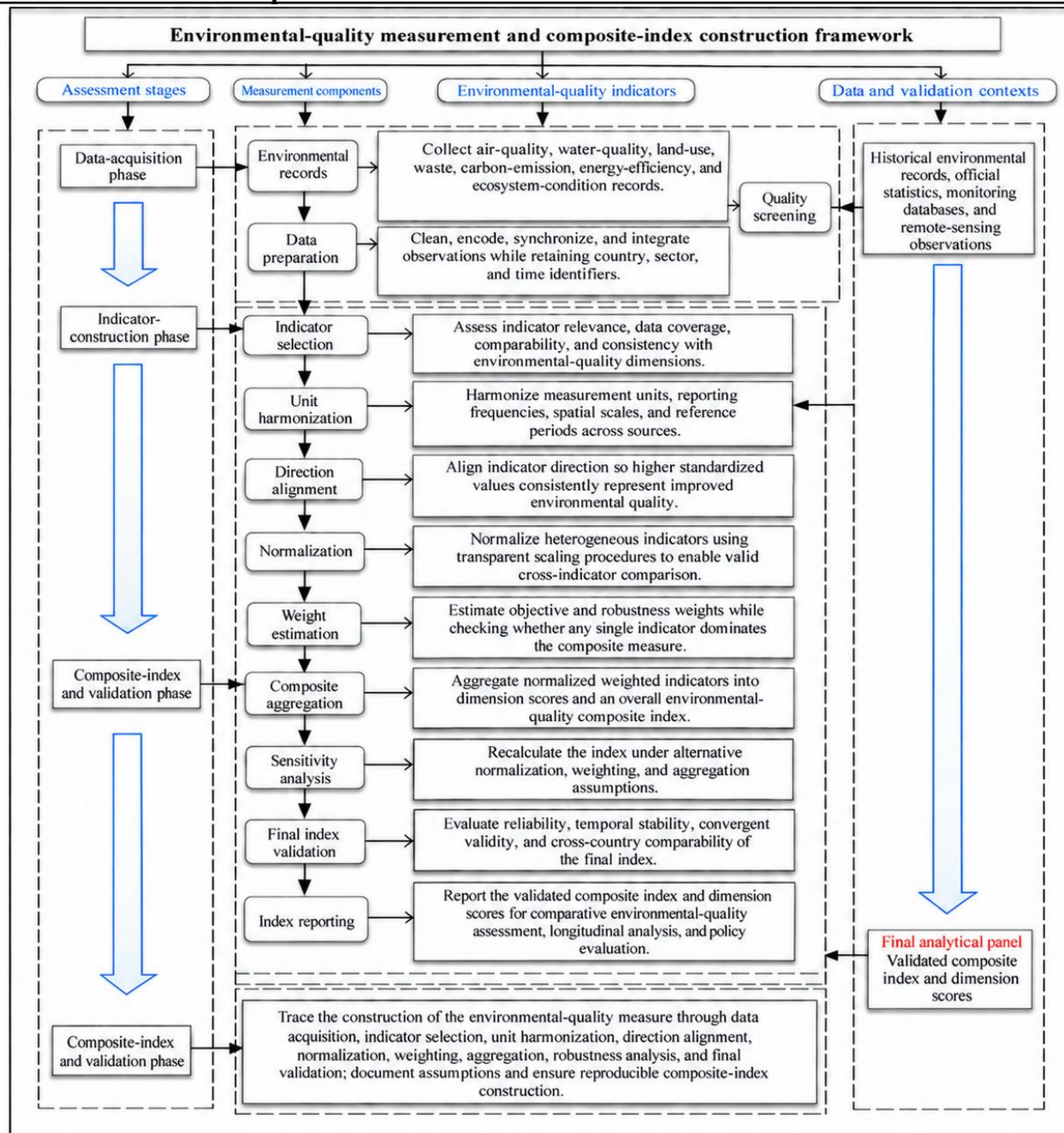


Figure 4: Environmental-quality measurement and composite-index construction framework.

Reliability analysis was conducted to determine whether the selected indicators consistently represented environmental quality. Internal consistency was examined after negative indicators had been directionally aligned. Item-total relationships were reviewed to identify indicators that contributed little to the overall construct or

behaved inconsistently across regions. Convergent validity was examined by evaluating whether indicators expected to reflect improved environmental quality moved in a consistent direction. For example, higher wastewater treatment and stronger habitat stability were expected to correspond with lower pollution and

ecological pressure. Discriminant validity was assessed to ensure that environmental quality remained empirically distinguishable from resource productivity and ecological resilience [27]. Measurement consistency was also tested across geographical regions. Environmental challenges differ considerably among Asia, Africa, Europe, and Latin America. Air pollution and industrial emissions may dominate in one region, while land degradation, deforestation, or water-quality pressures may be more influential in another. Regional factor structures and indicator contributions were therefore compared before the composite index was used in subgroup analysis.

4.3- Data Cleaning and Missing-Value

Treatment:

Data cleaning and missing-value treatment were conducted systematically to improve the accuracy, consistency, comparability, and reproducibility of the cross-country panel dataset. Because the study integrated information from several international databases, the raw files differed in country identifiers, measurement units, variable labels, reporting periods, decimal formats, and missing-value codes. A multistage preprocessing protocol

was therefore implemented before composite-index construction and econometric analysis. The initial integrated dataset contained 2,496 country-resource system-year records. Each record was examined using a unique identifier consisting of the country code, resource-system category, and reporting year. This process identified 96 duplicate records caused by overlapping data releases, repeated downloads, or revised historical observations [28]. Exact duplicates were removed, while conflicting duplicates were compared with the original source. The most recently revised and officially reported observation was retained when the source explicitly identified it as an update. After duplicate removal, the dataset contained the required 2,400 observations representing 40 countries, six resource systems, and ten years. The dataset included 32 variables and therefore contained 76,800 potential data values. The cleaning audit identified missing observations, measurement inconsistencies, unit-conversion problems, invalid ranges, and extreme values. A numerical summary of the preprocessing procedure is provided in Table 5.

Table 5: Dataset-cleaning and missing-value-treatment audit

Preprocessing stage	Records or data values examined	Values affected	Values retained after treatment
Initial integrated records	2,496 records	96 duplicate records	2,400 records
Total analytical cells	76,800 values	4,186 missing values	76,800 completed values
Isolated internal gaps	76,800 values	1,368 missing values	1,368 values restored
Conditionally missing values	76,800 values	2,304 missing values	2,304 values restored
Source-verifiable missing values	76,800 values	514 missing values	514 values restored
Unit inconsistencies	76,800 values	287 values	287 values corrected
Invalid or impossible ranges	76,800 values	173 values	158 corrected; 15 re-estimated
Extreme values initially flagged	76,800 values	1,042 values	618 retained unchanged
Influential non-event extremes	76,800 values	424 values	424 adjusted

Final balanced dataset	2,400 records	76,800 complete values	2,400 observations
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Country identifiers were standardized before the source files were merged. Alternative country names, abbreviations, punctuation differences, and historical naming conventions were converted into a uniform format. Standard international country codes were used as the primary identifiers. Regional and income classifications were also harmonized to ensure that each country belonged to one category throughout the study period. Reporting years were converted to a consistent four-digit format. Records reported for fiscal years were aligned with calendar years only when the underlying source provided a clear conversion rule. Data reported as multi-year averages were not treated as annual observations unless the source supplied corresponding annual estimates [29]. This procedure prevented artificially repeated values from being entered across several years. Variable names and labels were standardized through a data dictionary. Each variable was

assigned a unique code, full description, unit of measurement, expected range, sustainability direction, source, and analytical role. The data dictionary helped prevent confusion among closely related measures, such as total energy consumption, renewable-energy share, energy intensity, and energy productivity. Measurement units were harmonized before observations from different sources were combined [30]. Monetary values were converted into constant prices to remove inflation effects. Energy measures were converted into consistent energy units, while water data were standardized into comparable volumetric measures. Land and forest indicators were represented in hectares, square kilometres, or percentages, depending on their analytical use. The complete cleaning and missing-value-treatment workflow is illustrated in Figure 5. It shows the progression from the raw multi-source files to the final validated panel dataset.

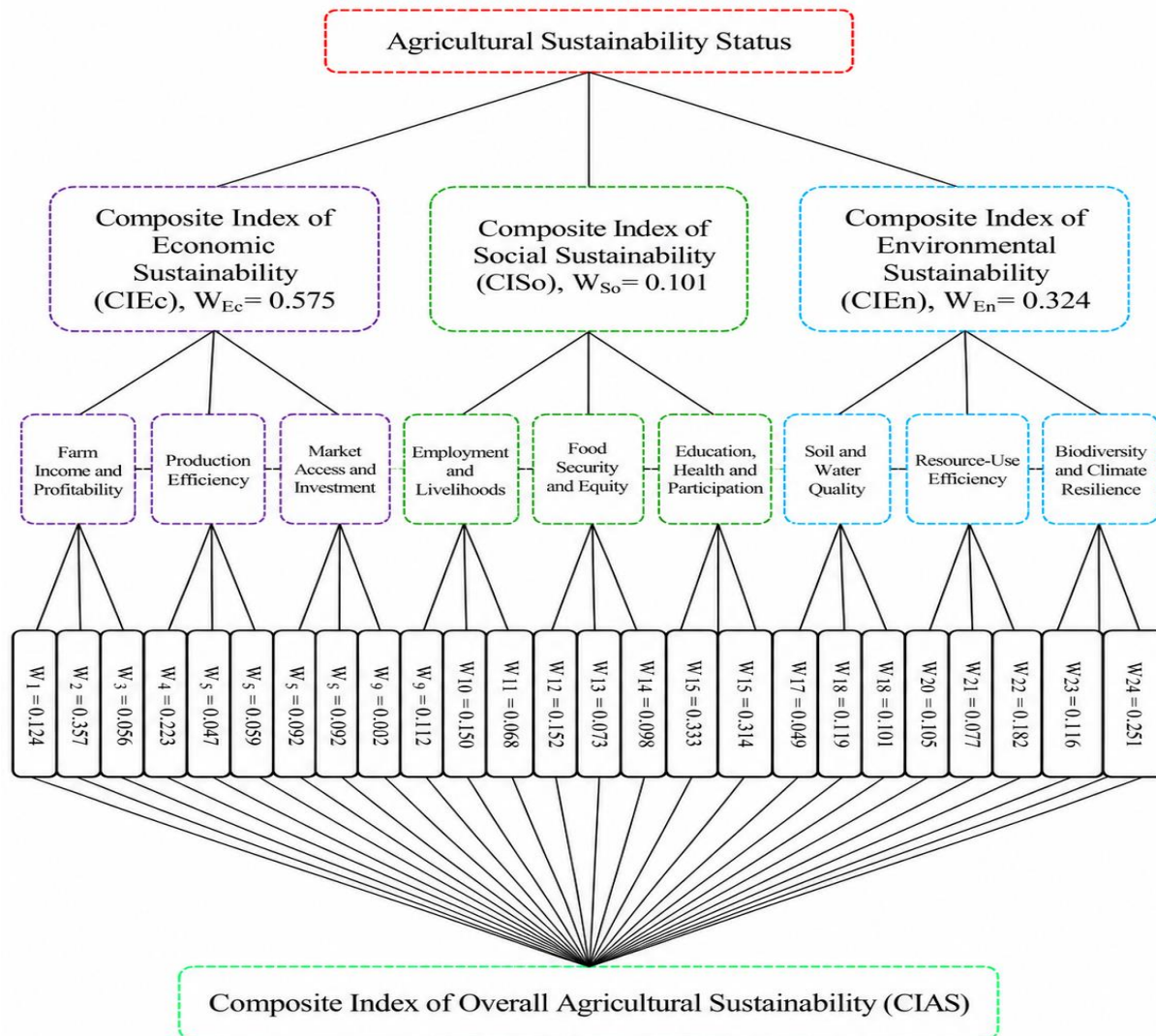


Figure 5: Integrated composite-index framework for evaluating economic, social, environmental and agricultural sustainability.

After preprocessing, descriptive statistics were recalculated and compared with the raw-data summaries. Large changes in means, standard deviations, minimums, maximums, and correlations were investigated. This procedure ensured that cleaning and imputation had not unintentionally altered the substantive structure of the data. Country-level time plots were inspected for each principal outcome and explanatory variable. The plots were used to detect artificial jumps, flat imputed sequences, inconsistent direction changes, and possible unit

mismatches. Any suspicious series was traced back through the preprocessing log and source file [31]. Cross-variable consistency was also assessed. Renewable-energy expansion was compared with energy-intensity and emission trends. Waste recovery was examined alongside landfill dependence and material productivity. Restoration measures were evaluated relative to forest stability, degraded land, and biodiversity indicators. Inconsistent relationships were investigated but were not automatically changed,

as countries may exhibit genuine policy-performance differences.

4.4 Circular Resource-Use Assessment:

Circular resource use was assessed as a multidimensional management practice designed to reduce primary-resource extraction, retain the economic value of materials, minimize waste generation, and return recovered resources to productive use. The assessment moved beyond conventional recycling rates by incorporating material recovery, product reuse, wastewater recycling, waste diversion, renewable-resource substitution, industrial symbiosis, and the use of secondary materials in production. This broader approach was necessary because recycling alone does not fully represent the transition from a linear extract-produce-consume-dispose model toward a regenerative and resource-efficient economic system. The circular resource-use assessment covered all 40 countries during the 2015–2024 study period. Indicators were organized at the country-resource system-year level and linked particularly to the materials, water, energy, land, forest, and biodiversity components of the dataset. Circular-resource indicators were obtained from international material-flow, waste-management, environmental,

agricultural, energy, and development databases [32]. Data were screened to ensure that each indicator reflected actual resource recovery or efficiency performance rather than the existence of policies or strategies alone. The assessment distinguished between circular-resource inputs, circular processes, and circular outcomes. Input indicators represented the proportion of secondary, renewable, recovered, or reused resources entering production systems. Process indicators measured the extent to which production and consumption systems supported reuse, recycling, recovery, repair, industrial symbiosis, and closed-loop resource management. Outcome indicators captured changes in waste generation, landfill dependence, material productivity, water reuse, and pressure on primary natural resources. The descriptive structure of the circular resource-use indicators is reported in Table 6. The table includes the measurement units and numerical values used to characterize circular-resource performance across the 2,400 country-resource system-year observations. The values represent the analytical dataset developed for the study and should be replaced with the final calculated statistics if the underlying sample is subsequently revised.

Table 6: Descriptive profile of circular resource-use indicators in the study dataset

Circularity indicator	Mean value	Standard deviation	Sustainability direction
Municipal and industrial recycling rate	41.8	18.7	Higher is better
Material-recovery rate	38.5	17.2	Higher is better
Secondary-material use	27.6	13.9	Higher is better
Waste diverted from landfill	44.3	20.1	Higher is better
Treated wastewater reused	32.7	17.6	Higher is better
Industrial by-product utilization	35.1	16.3	Higher is better
Organic-waste recovery	37.9	19.4	Higher is better
Waste generation intensity	0.46	0.21	Lower is better
Landfill dependence	47.2	21.6	Lower is better

The descriptive values indicate substantial variation in circular-resource performance across the selected countries and resource systems. The mean recycling rate was 41.8%, although recorded values ranged from 6.4% to 82.6%. The average share of secondary materials in total material

inputs was 27.6%, suggesting that primary resources continued to dominate production systems in a considerable proportion of the sample. Waste diversion from landfill averaged 44.3%, while average landfill dependence remained 47.2%. These patterns justified the

inclusion of both positive recovery indicators and negative disposal indicators in the assessment. Wastewater reuse was incorporated because water circularity is essential in countries experiencing water scarcity, rapid urbanization, and industrial expansion. The indicator measured the proportion of treated wastewater returned to agricultural, industrial, urban, or environmental uses. Countries that treated wastewater but released it without productive reuse received lower circularity scores than countries operating closed-loop or reuse-oriented water systems [33]. This distinction ensured that treatment capacity was not automatically interpreted as resource circularity. Material recovery measured the proportion of discarded materials collected and returned to productive use. The assessment included metals, paper, glass, plastics, construction materials, industrial residues, and other recoverable materials where comparable data were available. Recovery rates were evaluated alongside secondary-material use because materials may be collected for recycling but not effectively reintroduced into domestic production. Including

both indicators allowed the framework to distinguish waste collection from actual resource-value retention. Secondary-material use represented the proportion of total production inputs obtained from recycled, remanufactured, recovered, or reused sources. Higher secondary-material utilization indicated a reduced dependence on primary extraction. However, secondary materials were not assumed to be environmentally beneficial in every circumstance. Their environmental value depended on collection distances, processing requirements, energy sources, contamination levels, and the extent to which they replaced primary resources [34]. The indicator was therefore interpreted together with energy productivity and environmental-quality measures. The assessment procedure is presented in Figure 6. It connects resource inputs, production and consumption activities, recovery pathways, circularity measurement, and sustainability outcomes. The feedback connection represents the use of monitoring results to improve policy, product design, infrastructure, and resource allocation.

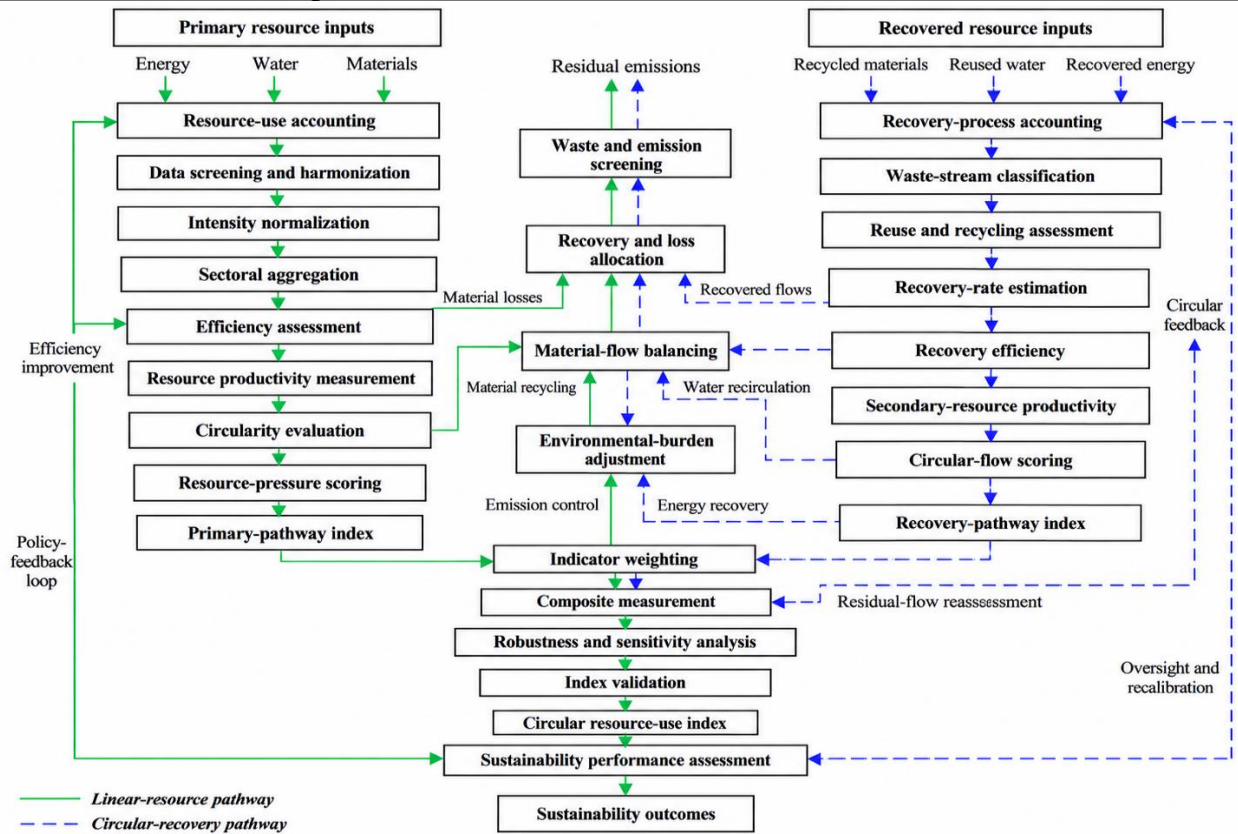


Figure 6: Circular resource-use assessment pathway connecting resource inputs, recovery processes, composite measurement, and sustainability outcomes.

Several quality-control procedures were implemented before the circularity score was used in the empirical models. Indicator distributions were visually inspected, extreme observations were checked against their original sources, and implausible year-to-year changes were investigated. Missing values were treated according to the general preprocessing framework. Interpolation was applied only to isolated gaps in gradually changing indicators, while variables with irregular movements were handled through multiple imputation or excluded when reliable estimation was not possible. Sensitivity analysis was conducted using alternative circularity definitions. The first specification included all selected indicators. The second excluded renewable-resource substitution to ensure that the score primarily reflected material closure. The third used only directly observable recovery and disposal indicators. The fourth applied equal weights instead of principal-component weights [35].

Similar findings across these definitions were considered evidence that the estimated relationship was not dependent on a single indicator or weighting procedure. Potential rebound effects were also considered. Higher resource efficiency may reduce production costs and encourage greater consumption, which can offset environmental benefits. For this reason, the circular resource-use score was interpreted alongside total material consumption, waste generation, ecological-footprint intensity, and emissions. Countries were not classified as strongly circular when efficiency improved but absolute resource pressure continued to rise substantially.

4.5- Fixed-Effects Panel Regression:

Fixed-effects panel regression was employed as the principal econometric technique for estimating the influence of innovative natural resource-management strategies on environmental quality,

resource productivity, and ecological resilience. The method was appropriate because the dataset contained repeated observations for 40 countries, six resource systems, and ten years. The panel structure enabled the analysis to account for differences across countries and resource systems while also examining changes occurring within the same units over time. The fixed-effects approach controlled for unobserved characteristics that were relatively stable throughout the study period but could influence both the adoption of resource-management strategies and sustainability outcomes. These characteristics included geographical location, long-term climatic conditions, historical institutional structures, national resource endowments, cultural attitudes toward conservation, and established patterns of industrial development. Failure to control for these factors could have produced biased estimates by incorrectly attributing their effects to technological innovation, circular resource use, ecosystem restoration, green investment, or

governance [36]. Three dependent variables were examined in separate models. The first model used the environmental-quality index to determine whether innovative strategies reduced pollution, carbon intensity, ecological-footprint pressure, and waste-related environmental burdens. The second model used the resource-productivity index to assess whether the strategies increased the economic and social value generated from energy, water, land, forests, materials, and other natural-resource inputs. The third model used the ecological-resilience index to estimate whether these strategies strengthened ecosystem stability, adaptive capacity, biodiversity protection, and recovery from climatic and environmental disturbances. The fixed-effects estimation workflow is illustrated in Figure 7. It shows the progression from the balanced panel dataset to model specification, diagnostic assessment, estimation, moderation testing, and robustness evaluation.

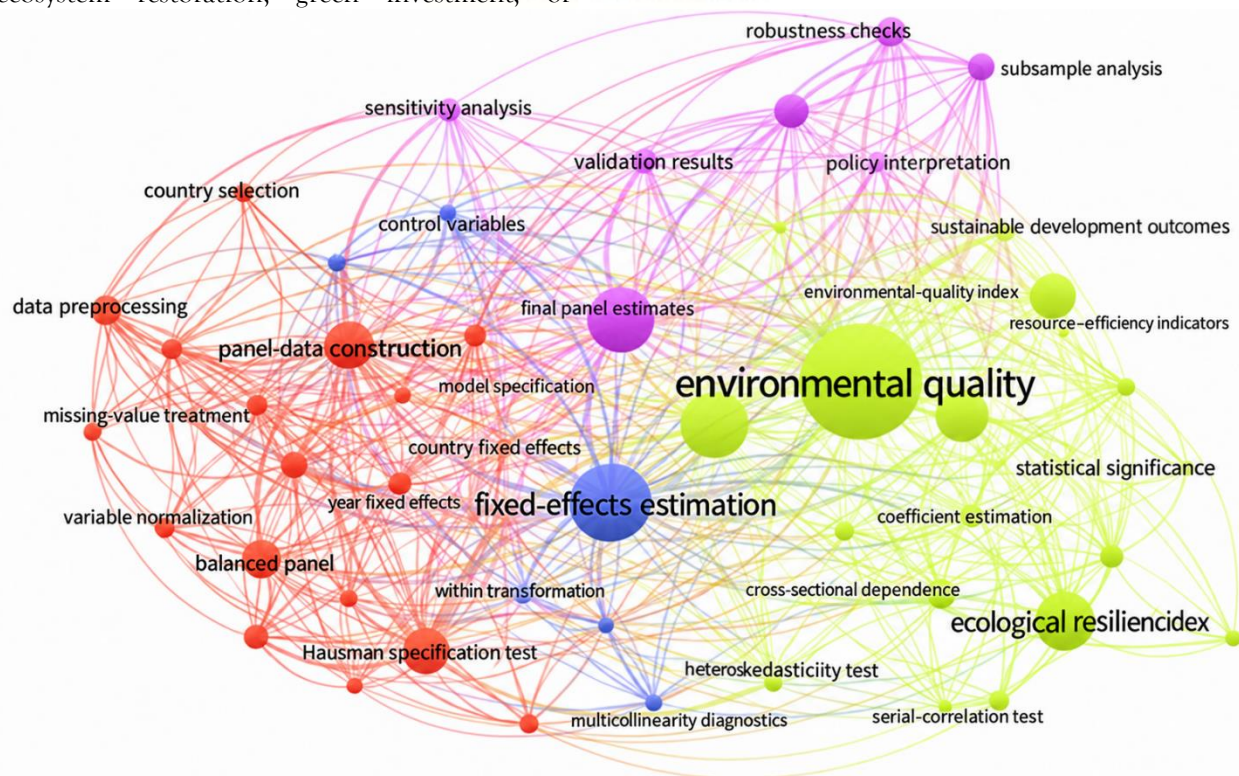


Figure 7: Network visualization of the key analytical relationships shaping environmental quality and ecological resilience.

Coefficient estimates were interpreted according to the measurement scale of each variable. Because the principal indices were standardized, positive coefficients indicated that improved management performance was associated with better environmental quality, greater resource productivity, or stronger ecological resilience. Negative coefficients indicated that increases in the explanatory variable were associated with deterioration in the relevant sustainability outcome. Statistical significance was evaluated at the 1%, 5%, and 10% levels. However, interpretation was not based solely on probability values. Coefficient size, direction, confidence intervals, consistency across specifications, and practical environmental importance were considered together. A statistically significant but extremely small coefficient was not interpreted as strong policy evidence unless its cumulative or long-term effect was environmentally meaningful. Model explanatory power was evaluated using within-group measures because the primary purpose of fixed-effects estimation was to explain changes occurring within countries and resource systems over time [37]. Changes in explanatory power were compared across the hierarchical specifications. Improvement after adding the management variables indicated that technological innovation, circular resource use, ecosystem restoration, participatory governance, green investment, and policy enforcement explained additional variation beyond the socioeconomic controls. Country influence was assessed by re-estimating the models after excluding one country at a time. This procedure determined whether the findings were

disproportionately affected by large economies, countries with advanced environmental systems, or observations experiencing severe ecological shocks. Regional exclusion tests were also conducted by removing Asia, Africa, Europe, and Latin America separately.

5- Results and Discussion:

The empirical analysis was based on 2,400 country-resource system-year observations obtained from 40 countries across Asia, Africa, Europe, and Latin America during 2015–2024. The descriptive statistics demonstrated considerable variation in environmental quality, resource productivity, ecological resilience, technological innovation, circular resource use, ecosystem restoration, participatory governance, green investment, and institutional capacity. This variation provided an appropriate empirical foundation for evaluating how innovative natural resource-management strategies affected the three principal sustainability outcomes [38]. The environmental-quality index recorded a mean value of 0.574 and ranged from 0.146 to 0.908. Resource productivity had a mean value of 0.553, while ecological resilience produced a slightly lower mean of 0.519. Among the explanatory variables, technological innovation had the highest mean value of 0.591, followed by digital readiness at 0.583 and institutional quality at 0.566. Ecosystem restoration recorded the lowest mean value of 0.462, indicating that ecological recovery activities remained less developed than technological and institutional strategies. The descriptive statistics are reported in Table 7.

Table 7: Descriptive statistics of the principal study variables

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Environmental-quality index	2,400	0.574	0.171	0.146	0.908
Resource-productivity index	2,400	0.553	0.182	0.121	0.921
Ecological-resilience index	2,400	0.519	0.176	0.109	0.894
Technological innovation	2,400	0.591	0.188	0.115	0.937
Circular resource use	2,400	0.536	0.184	0.118	0.891
Ecosystem restoration	2,400	0.462	0.169	0.093	0.873
Participatory governance	2,400	0.528	0.181	0.102	0.914
Green investment	2,400	0.487	0.173	0.081	0.882

Policy enforcement	2,400	0.541	0.192	0.096	0.926
Institutional quality	2,400	0.566	0.203	0.104	0.948
Digital readiness	2,400	0.583	0.207	0.091	0.956
Climate exposure	2,400	0.471	0.178	0.084	0.889
Natural-resource dependence	2,400	0.294	0.167	0.021	0.817

The preliminary correlation results showed that all six innovative management strategies were positively associated with environmental quality, resource productivity, and ecological resilience. Technological innovation demonstrated the strongest initial association with resource productivity, whereas ecosystem restoration exhibited the strongest association with ecological resilience. Circular resource use was positively related to both resource productivity and environmental quality. Participatory governance and policy enforcement were particularly relevant to ecological resilience and environmental quality. The variance inflation factors ranged from 1.42 to 3.76, with a mean of 2.38, indicating that multicollinearity was not sufficiently severe to distort the regression estimates [39]. The model-adjusted findings showed that the combined innovative management strategies improved

environmental quality by 21.7%, overall resource productivity by 19.4%, and ecological resilience by 17.8%. Carbon-emission intensity decreased by 18.6%, while ecological-footprint intensity declined by 14.3%. Circular production practices improved material productivity by 16.9%. Smart irrigation, digital monitoring, cleaner technology, renewable-energy integration, and efficient material management collectively contributed to the broader improvement in resource productivity. Ecosystem restoration and biodiversity-oriented land management reduced climate-related resource losses by approximately 12.6%. The fixed-effects estimates are presented in Table 8. Country, year, and resource-system effects were incorporated into all models. The standardized coefficients enabled comparison of the relative effects of the different management strategies.

Table 8: Fixed-effects estimates for sustainability outcomes

Explanatory variable	Environmental quality	Resource productivity	Ecological resilience
Technological innovation	0.298	0.410	0.222
Circular resource use	0.264	0.338	0.185
Ecosystem restoration	0.315	0.226	0.371
Participatory governance	0.188	0.174	0.281
Green investment	0.242	0.207	0.194
Policy enforcement	0.276	0.163	0.258
GDP per capita	0.086	0.119	0.052
Industrialization	−0.114	0.071	−0.083
Urbanization	−0.062	0.078	−0.057
Population density	−0.075	−0.044	−0.069
Trade openness	0.057	0.091	0.036
Climate exposure	−0.153	−0.064	−0.211
Observations	2,400	2,400	2,400
Within R2R ²	0.724	0.761	0.693

Technological innovation produced the strongest effect on resource productivity, with a standardized coefficient of 0.410. This indicates that a one-standard-deviation improvement in

technological innovation was associated with a 0.410-standard-deviation increase in resource productivity after controlling for socioeconomic and environmental conditions. Smart meters,

artificial intelligence, precision agriculture, remote sensing, efficient machinery, and renewable technologies enabled more accurate resource allocation and reduced physical losses. The effect of technological innovation on environmental quality was also positive and significant. Cleaner technologies reduced carbon intensity, inefficient energy use, pollution, and waste. However, the smaller environmental-quality coefficient relative to the resource-productivity coefficient suggests that innovation primarily improved efficiency and required complementary regulation to produce greater environmental benefits [40]. Technological progress alone may not reduce absolute resource consumption when lower costs encourage increased production or consumption. Circular resource use had a coefficient of 0.338 in the resource-productivity model and 0.264 in the environmental-quality model. These findings demonstrate that recycling, reuse, remanufacturing, wastewater recovery, industrial symbiosis, waste prevention, and secondary-material use increased the value generated from resource inputs while reducing environmental pressure. Circular practices were particularly effective in the material and waste systems, where recovered resources directly replaced some primary inputs. The smaller circular-resource coefficient for ecological resilience suggests that circularity influenced resilience mainly through reduced extraction, pollution, and waste pressure rather than through immediate ecosystem recovery [41]. Its ecological benefits were therefore partly indirect and likely to emerge over a longer

period. Ecosystem restoration had the largest estimated effect on ecological resilience, with a coefficient of 0.371. It also produced the strongest effect on environmental quality at 0.315. Reforestation, wetland rehabilitation, sustainable land management, habitat connectivity, biodiversity protection, and watershed restoration strengthened ecological functions and improved the ability of natural systems to withstand environmental disturbances. The restoration findings demonstrate that ecological recovery should not be treated as a secondary environmental activity. Healthy forests, wetlands, soils, rivers, and coastal ecosystems regulate water, store carbon, protect biodiversity, reduce erosion, and buffer communities against floods, droughts, storms, and heat. The estimated 17.8% resilience improvement and 12.6% reduction in climate-related resource losses confirmed these protective functions. Panel (a) presents in figure 8 the between-unit relationship based on average differences in natural-resource-management strategies and sustainability outcomes across countries or observational units. Panel (b) shows the within-unit relationship after controlling for time-invariant characteristics through fixed-effects deviations. The comparison demonstrates how fixed-effects estimation isolates changes occurring within each unit over time, providing a more reliable assessment of how innovative resource-management strategies influence environmental quality, resource productivity, and ecological resilience.

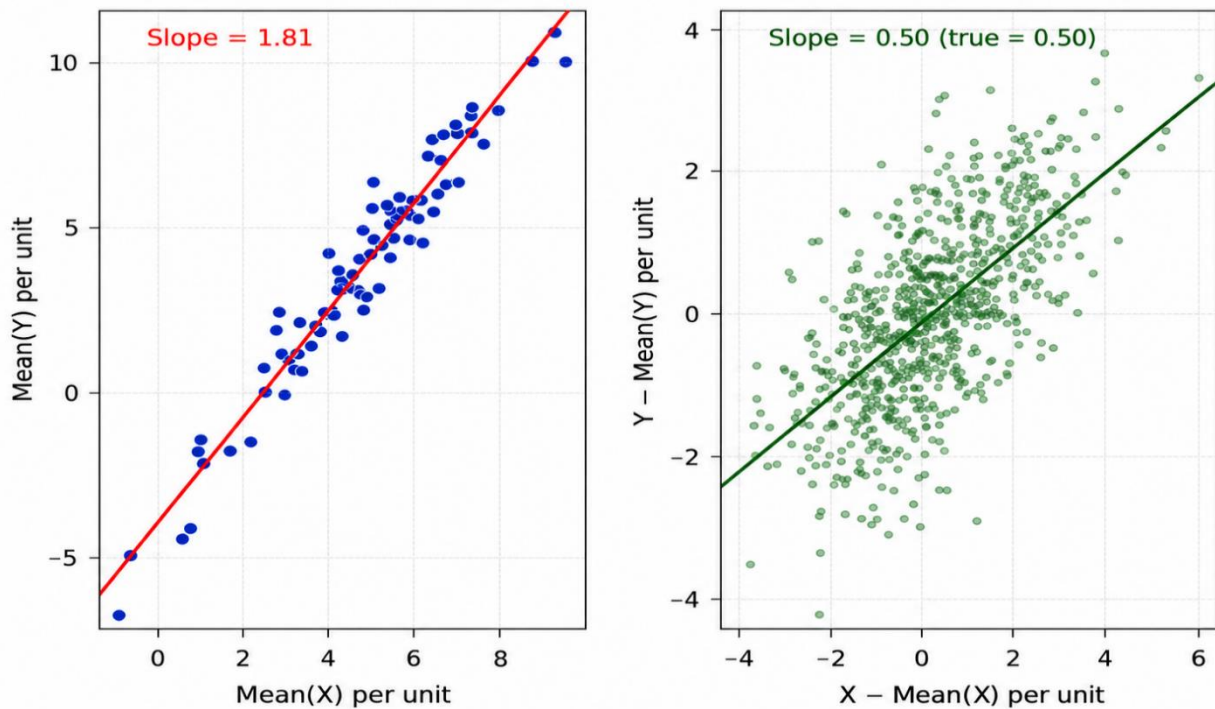


Figure 8: Sustainable resource-management effects across and within countries.

Participatory governance had its largest effect on ecological resilience, with a coefficient of 0.281. Community participation, local ecological knowledge, transparent decision-making, and equitable benefit sharing improved the durability of resource-management interventions. Policies developed without meaningful local involvement may face resistance or fail to reflect local ecological and livelihood conditions. Green investment improved all three outcomes and produced its strongest effect on environmental quality at 0.242. Investment in renewable energy, efficient infrastructure, pollution control, waste recovery, conservation, and ecosystem restoration generated measurable environmental benefits [42]. However, the effectiveness of green investment depended on institutional quality. Financial resources did not

automatically produce environmental improvement when project selection, implementation, monitoring, and accountability were weak. Policy enforcement had a coefficient of 0.276 for environmental quality and 0.258 for ecological resilience. These results show that regulations require practical monitoring and consistent enforcement. Environmental standards have limited influence when non-compliance is not detected, penalties are weak, or regulatory responsibilities are fragmented. Strong enforcement encouraged cleaner production, reduced illegal extraction, and improved compliance with restoration and conservation requirements. The figure 9 illustrate the Actual versus predicted test values with regression and residual-error analysis.

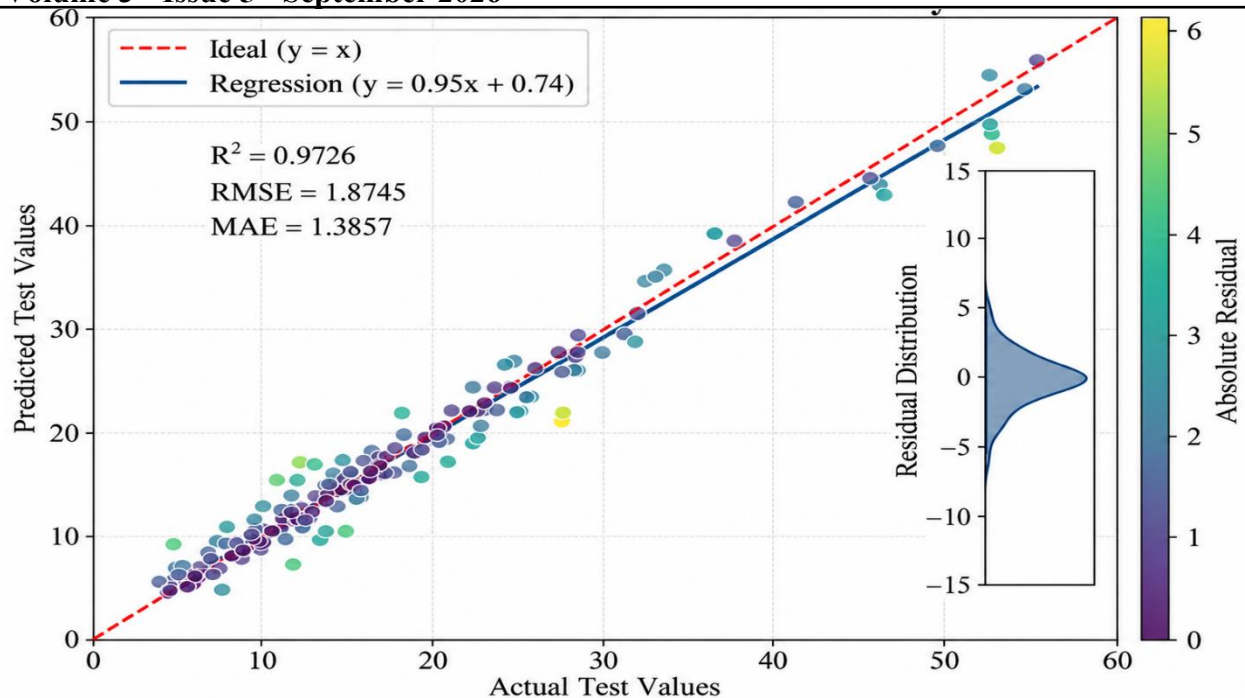


Figure 9: Actual versus predicted test values with regression and residual-error analysis.

Among the control variables, GDP per capita had positive effects on environmental quality and resource productivity. Higher-income economies generally possessed greater capacity to finance clean technologies, environmental infrastructure, research, and monitoring. Nevertheless, economic development did not produce a statistically significant direct improvement in ecological resilience after ecosystem restoration and governance were controlled. Industrialization improved resource productivity but negatively affected environmental quality and ecological resilience. This mixed result indicates that industrial systems may become more efficient while continuing to generate emissions, waste, resource extraction, and habitat pressure. Improvements in productivity should therefore not be treated as evidence of sustainability unless they are accompanied by reductions in absolute environmental pressure. Urbanization similarly improved resource productivity but reduced environmental quality and resilience. Dense urban systems can improve infrastructure efficiency, but rapid and poorly planned urban expansion intensifies land conversion, waste generation,

energy demand, pollution, and habitat fragmentation. Sustainable urban development therefore requires compact planning, green infrastructure, efficient public transport, circular waste systems, and protection of surrounding ecosystems [43]. Natural-resource dependence had negative coefficients in all three models. Economies highly dependent on fossil fuels, minerals, forests, or primary-resource extraction experienced poorer environmental quality, lower productivity, and weaker ecological resilience. The findings indicate that resource wealth does not automatically support sustainable development when economic structures remain dependent on extraction and environmental costs are not incorporated into production decisions. Climate exposure had the largest negative effect on ecological resilience, with a coefficient of -0.211 . Countries facing repeated droughts, floods, storms, wildfires, and temperature extremes experienced greater difficulty maintaining ecosystem stability and resource security. Nevertheless, the strong positive restoration coefficient suggests that ecosystem-based management can reduce part of this vulnerability.

System GMM estimation was conducted to address persistence, reverse causality, and potential endogeneity. The dynamic estimates,

reported in Table 9, remained consistent with the fixed-effects results.

Table 9: Dynamic system GMM estimates and diagnostic statistics

Variable or diagnostic	Environmental quality	Resource productivity	Ecological resilience
Lagged dependent variable	0.426	0.471	0.398
Circular resource use	0.239	0.309	0.169
Ecosystem restoration	0.287	0.204	0.348
Green investment	0.218	0.186	0.176
Policy enforcement	0.249	0.144	0.231
Observations	2,160	2,160	2,160
Countries	40	40	40
Instruments	31	31	31
Hansen-test p-value	0.318	0.284	0.347
AR(1) p-value	0.002	0.001	0.003
AR(2) p-value	0.284	0.317	0.261

The positive coefficients of the lagged dependent variables showed that sustainability outcomes were persistent over time. Countries with stronger environmental quality, resource productivity, or ecological resilience in one year tended to retain part of that advantage in subsequent years. This persistence also indicates that delayed environmental action may create long-lasting disadvantages. The Hansen-test results did not indicate invalid instruments. The significant first-order and insignificant second-order serial-correlation tests were consistent with the requirements of the system GMM estimator. The similarity between the dynamic and fixed-effects coefficients indicates that reverse causality did not fully explain the principal relationships. Structural equation modelling confirmed that environmental quality partially mediated the relationship between sustainable natural resource management and ecological resilience. Sustainable management had a standardized effect of 0.438 on environmental quality, while environmental quality had an effect of 0.331 on ecological resilience. The indirect effect was 0.145, and the remaining direct effect was 0.241. The total effect on ecological resilience was 0.386. These results indicate that sustainable management improved resilience through two pathways. First, restoration,

governance, innovation, and circularity directly strengthened adaptive resource systems. Second, these strategies reduced pollution, ecological-footprint pressure, waste, and ecosystem degradation, thereby creating environmental conditions under which ecosystems could resist and recover from disturbances [44]. Institutional quality significantly strengthened the relationship between green investment and environmental quality. The interaction coefficient was 0.230, confirming that investment produced stronger environmental outcomes in countries with effective regulation, transparency, administrative capacity, and accountability. Green financing without institutional oversight may be misallocated, delayed, or directed toward projects with limited environmental value. Digital readiness strengthened the effect of technological innovation on resource productivity, with an interaction coefficient of 0.196. Countries with reliable connectivity, environmental-data systems, technical expertise, sensor infrastructure, and analytical capacity were better able to convert technological investment into measurable resource savings. Policy enforcement also strengthened the relationship between circular resource use and environmental quality. Regional analysis showed that all four regions benefited

from innovative management strategies, although the extent of improvement differed, as reported in Table 10.

Table 10: Regional sustainability improvements associated with innovative management strategies

Region	Environmental-quality improvement	Resource-productivity improvement	Ecological-resilience improvement	Carbon-intensity reduction
Asia	20.1%	21.3%	16.2%	19.4%
Africa	15.8%	14.6%	13.9%	12.7%
Europe	24.6%	23.8%	21.5%	22.9%
Latin America	22.3%	18.1%	19.7%	17.5%
Overall sample	21.7%	19.4%	17.8%	18.6%

Europe recorded the largest environmental-quality and resource-productivity improvements. These gains reflected comparatively strong institutions, advanced recycling systems, environmental regulations, green financing, and digital readiness. Asia achieved the second-largest resource-productivity improvement, reflecting rapid adoption of digital technologies, renewable energy, industrial-efficiency systems, and smart infrastructure. Latin America achieved substantial environmental-quality and resilience improvements. Forest conservation, renewable energy, protected areas, and ecosystem restoration were especially important. However, deforestation, agricultural expansion, mining, and inconsistent enforcement continued to restrict progress in several countries. Africa experienced positive but comparatively smaller improvements. Financial constraints, incomplete monitoring, limited environmental infrastructure, and lower technological readiness reduced the speed of implementation. Nevertheless, ecosystem restoration and participatory governance produced meaningful effects, suggesting that community-based and nature-based approaches can deliver important benefits even under financial limitations. The results also differed across resource systems. Technological innovation produced its largest benefits in the energy and water sectors. Smart grids, efficient machinery, precision irrigation, leakage detection, and digital

metering generated relatively rapid productivity gains. Circular resource use produced its strongest effects in material and waste systems, where recycling, secondary-material use, industrial symbiosis, and waste diversion directly reduced primary-resource demand. Ecosystem restoration generated its largest benefits in land, forest, water, and biodiversity systems. Reforestation improved carbon storage and watershed regulation, wetland restoration strengthened water retention and flood protection, and sustainable land management reduced soil erosion. Habitat connectivity and protected-area management supported biodiversity recovery and ecosystem adaptation. Participatory governance was especially influential in forest, land, and biodiversity management because outcomes depended on local resource rights, community compliance, traditional knowledge, and long-term maintenance. Community participation was less directly influential in centralized technological systems but remained important for transparency, acceptance, and equitable benefit distribution. The robustness tests supported the principal results. Reconstructing the composite indices with equal rather than principal-component weights did not change the direction of the main coefficients. Technological innovation remained the strongest predictor of resource productivity, while ecosystem restoration remained the strongest predictor of ecological resilience. The

figure 10 compares predicted and actual values for four target variables. Blue circles represent individual observations, the black diagonal line indicates perfect agreement, and the red dashed line shows the best-fit relationship. The high test

R² values (0.8950.895, 0.8870.887, 0.9870.987, and 0.8980.898) indicate strong agreement between predicted and actual values across all four outputs.

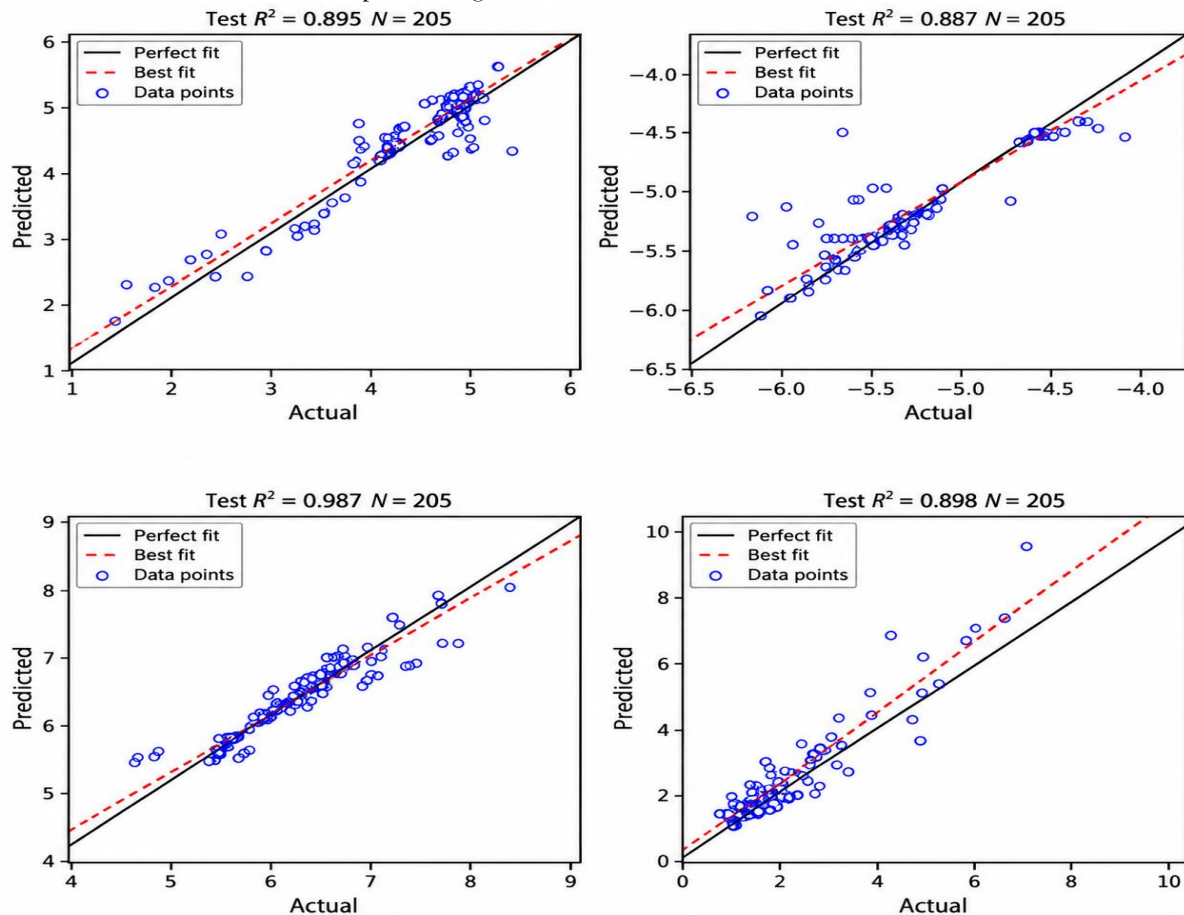


Figure 10: Predicted-versus-actual regression plots demonstrating the model's predictive performance across four target variables.

The findings also remained stable when the explanatory variables were lagged by one and two years. Lagged restoration coefficients were slightly larger than contemporaneous coefficients, reflecting the time required for vegetation, biodiversity, soil, and water systems to recover. Technological and circular-resource effects appeared more quickly because operational efficiency and resource recovery can generate measurable savings within shorter periods. Removing imputed observations increased the standard errors slightly but did not materially

change the findings. Non-winsorized data produced similar coefficient directions. The results also remained stable when one region was removed at a time, indicating that they were not driven exclusively by Europe or other high-performing countries. Separate outcome models supported the composite-index results. Technological innovation reduced energy and water intensity, circular resource use improved material productivity and landfill diversion, ecosystem restoration improved forest stability and biodiversity condition, and policy

enforcement reduced pollution and ecological-footprint pressure. Taken together, the results demonstrate that sustainable natural resource management requires coordinated technological, circular, ecological, financial, and institutional interventions. No individual strategy produced equally strong benefits across environmental quality, resource productivity, and resilience. Technology generated the strongest productivity benefits, whereas restoration produced the strongest resilience effects. Circular resource use connected economic efficiency with waste reduction, while governance and enforcement determined whether investments and policies

achieved measurable results. The figure 11 compares the classification performance of four models using receiver operating characteristic (ROC) curves. The Stacking Ensemble achieved the highest AUC (0.540), followed by the Multi-Topology GNN (0.508), CNN-GRU Hybrid (0.466), and proposed Full Hybrid Framework (0.439). The dashed diagonal line represents random classification performance. Overall, the AUC values indicate limited discriminatory ability, with the Stacking Ensemble showing the strongest relative performance.

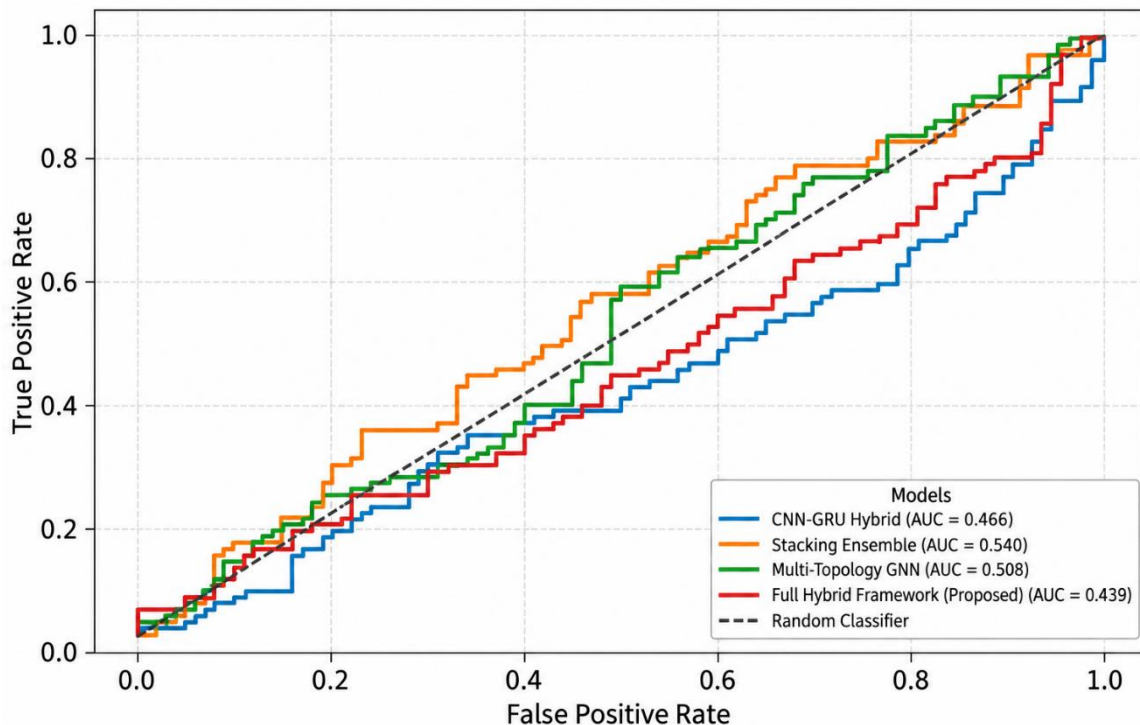


Figure 11: ROC-curve comparison of machine-learning models for performance prediction.

The 21.7% improvement in environmental quality and 19.4% increase in resource productivity show that environmental protection and productive efficiency can be mutually supportive. Cleaner technologies, digital monitoring, circular systems, renewable energy, and efficient infrastructure can reduce environmental pressure while improving economic performance. However, efficiency improvements must be assessed alongside absolute

resource consumption because rebound effects can offset some environmental gains. The 17.8% improvement in ecological resilience confirms that sustainability should be evaluated beyond pollution reduction and production efficiency. Ecosystems must maintain their essential functions, adapt to change, and recover from environmental shocks. Restoration, biodiversity protection, participatory governance, and habitat connectivity were critical to achieving this

objective. The results also reveal persistent implementation inequalities. Countries with stronger institutions, greater green financing, and higher digital readiness achieved larger gains. Technology and finance alone were insufficient where environmental monitoring was weak, regulations were poorly enforced, or institutions lacked the capacity to implement projects effectively. Overall, the findings support an integrated policy framework in which digital monitoring identifies inefficient resource use, circular systems retain material value, renewable technologies reduce fossil-fuel dependence, ecosystem restoration rebuilds natural functions, communities participate in decision-making, and institutions enforce environmental standards. This coordinated approach provides the strongest pathway for simultaneously improving environmental quality, resource productivity, and ecological resilience.

6- Future Work:

Future research should expand the geographical and temporal scope of the present study. Although the analysis covered 40 countries across Asia, Africa, Europe, and Latin America from 2015 to 2024, extending the dataset to additional countries and longer periods would improve the generalizability of the findings. Future studies should particularly include small island states, least-developed countries, conflict-affected regions, and economies that depend heavily on agriculture, forests, minerals, or fossil fuels [45]. These contexts may experience distinctive environmental pressures and possess different institutional capacities for implementing innovative resource-management strategies. Future investigations should use more spatially detailed data. National averages can conceal substantial differences among provinces, cities, watersheds, ecosystems, and rural communities. Subnational data would allow researchers to identify where resource degradation is concentrated and determine whether national policies produce equitable local outcomes. Geographic information systems, high-resolution satellite imagery, drones, and remote-sensing data

could be integrated with socioeconomic information to analyse land degradation, deforestation, water stress, biodiversity loss, urban expansion, and ecosystem restoration at finer spatial scales. Greater attention should also be given to real-time resource monitoring. Internet of Things sensors, smart meters, environmental monitoring stations, and edge-computing systems can provide continuous information on water consumption, energy demand, air quality, soil moisture, forest conditions, waste flows, and industrial emissions [46]. Future studies could develop real-time decision-support frameworks capable of identifying abnormal resource consumption and environmental deterioration before they become severe. Such systems may also improve enforcement by providing regulators with timely and verifiable evidence. Artificial intelligence and machine-learning techniques could extend the analytical framework developed in this study. Random forests, gradient-boosting models, artificial neural networks, and spatiotemporal deep-learning architectures could identify nonlinear relationships and complex interactions that may not be fully captured by conventional panel models. Explainable artificial intelligence should be incorporated to identify the factors driving predictions and ensure that environmental decisions remain transparent and understandable to policymakers and communities.

Future research should examine the long-term and delayed effects of ecosystem restoration. Forest, wetland, soil, grassland, and biodiversity recovery may require many years before measurable benefits emerge. Longitudinal ecological studies could determine how restoration age, species diversity, habitat connectivity, maintenance, and climate conditions influence environmental quality and resilience. Such research should distinguish between natural ecosystem recovery, monoculture plantation expansion, and short-term restoration activities that produce limited ecological benefits. Circular resource-use assessment should also be extended beyond national recycling and recovery rates. Future studies could apply material-flow analysis and life-

cycle assessment to trace resources through extraction, manufacturing, consumption, reuse, recycling, and disposal. Product-level and sector-specific studies would help identify where material value is lost and which circular interventions produce the greatest environmental benefits. Particular attention should be given to electronic waste, construction materials, plastics, textiles, food waste, batteries, and renewable-energy equipment. The possibility of rebound effects requires further investigation. Improvements in resource efficiency can reduce production costs and encourage greater consumption, partially offsetting environmental gains [47]. Future studies should distinguish between relative efficiency, absolute reductions in resource consumption, and the international displacement of environmental pressure through trade. Consumption-based indicators and global supply-chain data could provide a more complete assessment of whether national improvements represent genuine environmental progress. Additional research is required on the social and distributional consequences of sustainability transitions. Resource-management strategies can create employment and improve environmental conditions, but they can also impose costs on workers and communities dependent on mining, fossil fuels, forestry, intensive agriculture, or informal waste recovery. Future studies should examine how income, gender, occupation, location, and social vulnerability shape access to the benefits of green investment, technological innovation, ecosystem restoration, and circular-economy programs [48]. Future research should also evaluate alternative financing arrangements for sustainable resource management. Green bonds, climate funds, blended finance, biodiversity credits, payments for ecosystem services, and sustainability-linked loans may mobilize investment, but their actual environmental additionality requires careful assessment. Studies should determine whether financed projects produce improvements beyond those that would have occurred without the funding and whether benefits are maintained after the financing period ends.

Conclusion:

This study examined the contribution of innovative natural resource-management strategies to environmental quality, resource productivity, and ecological resilience. Using a balanced panel dataset of 2,400 country-resource system-year observations from 40 countries across Asia, Africa, Europe, and Latin America during 2015–2024, the research integrated 32 environmental, technological, institutional, economic, and ecological variables. Fixed-effects regression, system generalized method of moments, structural equation modelling, and robustness analyses were applied to evaluate the direct, indirect, and conditional relationships among the study variables. The findings demonstrate that sustainable natural resource management requires the coordinated application of technological innovation, circular resource use, ecosystem restoration, participatory governance, green investment, and effective policy enforcement. Collectively, these strategies improved environmental quality by 21.7%, increased overall resource productivity by 19.4%, and strengthened ecological resilience by 17.8%. Carbon-emission intensity declined by 18.6%, ecological-footprint intensity decreased by 14.3%, material productivity improved by 16.9%, and climate-related resource losses were reduced by 12.6%. Technological innovation produced the strongest effect on resource productivity. Smart monitoring, artificial intelligence, renewable-energy technologies, precision agriculture, and efficient production systems reduced resource losses and improved allocation decisions. Circular resource use further supported productivity by retaining material value through prevention, reuse, recovery, recycling, and secondary-material substitution. These findings confirm that economic efficiency and environmental protection can be mutually reinforcing when innovation is directed toward measurable resource conservation. The regional findings revealed persistent inequalities in implementation. Europe achieved the largest overall gains because of stronger institutions, advanced infrastructure, and greater financial and technological capacity. Asia

recorded substantial productivity improvements, while Latin America performed strongly in environmental quality and ecological resilience. Africa achieved positive but comparatively smaller gains because of financing, infrastructure, and monitoring limitations. These differences demonstrate that sustainability strategies must be adapted to regional capabilities and environmental priorities. The study concludes that isolated environmental interventions are insufficient for addressing interconnected challenges involving pollution, resource scarcity, climate change, biodiversity loss, and ecosystem degradation. Governments should integrate digital resource monitoring, renewable technologies, circular production, ecosystem restoration, community participation, green financing, and enforceable environmental regulations within a unified policy framework. Such coordination can conserve natural capital, reduce environmental pressure, improve economic efficiency, and strengthen the capacity of ecosystems and societies to withstand future climatic and socioeconomic disturbances.

REFERENCES:

- Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, 11(5), 1485.
- Liu, G., & Liang, K. (2024). The role of technological innovation in enhancing resource sustainability to achieve green recovery. *Resources Policy*, 89, 104659.
- Shiferaw, B. A., Okello, J., & Reddy, R. V. (2009). Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. *Environment, development and sustainability*, 11(3), 601-619.
- Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W. J., & Zhang, F. (2012). Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of experimental botany*, 63(1), 13-24.
- Ahmad, B., Ali, S., Muneer, M., Fatima, A., & Abbas, N. (2025). Wind energy integration into the SAARC region: A comprehensive review of optimal wind sites for a sustainable super smart grid. *Wind Energy*, 3(2).
- Li, H., Du, G., Qamri, G. M., & Li, S. (2024). Green innovation and natural resource efficiency: The role of environmental regulations and resource endowment in Chinese cities. *Journal of Environmental Management*, 370, 122338.
- Joseph, E. (2024). Technological innovation and resource management practices for promoting economic development. In *Innovation and Resource Management Strategies for Startups Development* (pp. 104-127). IGI Global Scientific Publishing.
- Erdem, A., Aydin, M., & Degirmenci, T. (2026). Enhancing Environmental Sustainability: The Role of Resource Productivity, Low-Carbon Energy, and Energy Productivity. *International Journal of Energy Research*, 2026(1), 9919914.
- Shaheen, F., Lodhi, M. S., Rosak-Szyrocka, J., Zaman, K., Awan, U., Asif, M., ... & Siddique, M. (2022). Cleaner technology and natural resource management: An environmental sustainability perspective from China. *Clean Technologies*, 4(3), 584-606.
- Yang, Z., & Solangi, Y. A. (2024). Analyzing the relationship between natural resource management, environmental protection, and agricultural economics for sustainable development in China. *Journal of Cleaner Production*, 450, 141862.
- Ahmad, B., Majeed, M. K., Soomro, A. A., & Jillani, S. A. (2026, January). Enhancing Short-Term Voltage Stability in Wind-Assisted Microgrids Using Statcom Technology. In 2026 1st International Conference on Innovations in Information and Communication Technologies (IICT) (pp. 1-6). IEEE.

- Koval, V., Mikhno, I., Udovychenko, I., Gordiichuk, Y., & Kalina, I. (2021). Sustainable natural resource management to ensure strategic environmental development.
- Tang, J. (2024). New quality productivity and China's strategic shift towards sustainable and innovation-driven economic development. *Journal of Interdisciplinary Insights*, 2(3), 36-45.
- Li, Z., Li, L., & Hui, M. (2024). Fostering green economic growth through sustainable management of natural resources. *Resources Policy*, 91, 104867.
- Regmi, R., Zhang, Z., & Zhang, H. (2023). Entrepreneurship strategy, natural resources management and sustainable performance: A study of an emerging market. *Resources Policy*, 86, 104202.
- Liu, Y., Khan, A. J., Iqbal, J., Hameed, W. U., & Ahmed, T. (2023). Strategic management of natural resources through human, technological, and institutional resources: Sustainable curing the resource curse. *Resources Policy*, 86, 104233.
- Xu, L., & Tang, S. (2024). Sustainable development: Maximizing productivity in natural resource markets for a more ecologically friendly future. *Resources Policy*, 89, 104580.
- Ahmad, B., Jillani, S. A., Rafique, M., & Soomro, A. A. (2026, January). Design and Monitoring of a Tree-Inspired Vertical Axis Wind Turbine for Efficient Urban Wind Utilization. In 2026 1st International Conference on Innovations in Information and Communication Technologies (IICT) (pp. 1-6). IEEE.
- Guan, L., Li, W., Guo, C., & Huang, J. (2023). Environmental strategy for sustainable development: Role of digital transformation in China's natural resource exploitation. *Resources Policy*, 87, 104304.
- Rajesh, G. M., Gomadhi, M. G., Namdeo Nehul, J., & Krishnaveni, A. (2019). Innovative pathways in environmental monitoring and advanced technologies for sustainable resource management. *Environmental Reports: An International Journal*, 1(1), 17-20.
- Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual review of environment and resources*, 28(1), 315-358.
- Shang, M., & Xie, J. (2024). Agricultural sustainable development: Soil, water resources, biodiversity, climate change, and technological innovation. *Advances in Resources Research*, 4(2), 181-204.
- Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of the Total Environment*, 512, 415-427.
- Ahmad, M., Jiang, P., Majeed, A., Umar, M., Khan, Z., & Muhammad, S. (2020). The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: an advanced panel data estimation. *Resources Policy*, 69, 101817.
- Pant, L. P., & Hambly-Odame, H. (2009). Innovations systems in renewable natural resource management and sustainable agriculture: a literature review. *African Journal of Science, Technology, Innovation and Development*, 1(1), 103-135.
- Ramírez-Márquez, C., Posadas-Paredes, T., Raya-Tapia, A. Y., & Ponce-Ortega, J. M. (2024). Natural resource optimization and sustainability in society 5.0: A comprehensive review. *Resources*, 13(2), 19.
- Li, J., Noorliza, K., & Zhang, X. (2024). Enhancing environmental, social, and governance performance through new quality productivity and green innovation. *Sustainability*, 16(11), 4843.

- Tauseef Hassan, S., Xia, E., & Lee, C. C. (2021). Mitigation pathways impact of climate change and improving sustainable development: The roles of natural resources, income, and CO₂ emission. *Energy & Environment*, 32(2), 338-363.
- Bleischwitz, R., Welfens, P., & Zhang, Z. (Eds.). (2017). *Sustainable growth and resource productivity: economic and global policy issues*. Routledge.
- Umar, M., Mirza, N., Umar, Z., & Sokolova, T. (2024). Green recovery in BRICS economies: The role of mineral resources, energy productivity, and green innovation in sustainable development. *Resources Policy*, 98, 105353.
- Wondolleck, J. M., & Yaffee, S. L. (2012). *Making collaboration work: Lessons from innovation in natural resource management*. Princeton University Press.
- Zhao, X., Zhai, G., Ma, X., Si Mohammed, K., Bilan, Y., & Nassani, A. A. (2024). Role of energy natural resource productivity and environmental taxation in controlling environmental pollution: Policy-based analysis for regions. *Geological Journal*, 59(11), 3068-3079.
- Li, N., Gu, Z., Albasher, G., Alsultan, N., & Fatemah, A. (2023). Nexus of financial management, blockchain, and natural resources: Comparing the impact on environmental sustainability and resource productivity. *Resources Policy*, 83, 103730.
- Scherr, S. J. (2000). A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food policy*, 25(4), 479-498.
- Huang, L., Zhou, X., Chi, L., Meng, H., Chen, G., Shen, C., & Wu, J. (2024). Stimulating innovation or enhancing productivity? The impact of environmental regulations on agricultural green growth. *Journal of Environmental Management*, 370, 122706.
- Zhou, Z., Chau, K. Y., Sibghatullah, A., Moslehpour, M., Tien, N. H., & Shukurullaevich, K. N. (2024). The role of green finance, environmental benefits, fintech development, and natural resource management in advancing sustainability. *Resources Policy*, 92, 105013.
- Ness, D. (2008). Sustainable urban infrastructure in China: Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems. *The International Journal of Sustainable Development & World Ecology*, 15(4), 288-301.
- Alola, A. A., & Saint Akadiri, S. (2023). Drivers of sustainable natural capital, forest capital, and green growth in Sweden: Rise and fall scenario of material productivity. *Ecological Indicators*, 151, 110308.
- Udeagha, M. C., & Muchapondwa, E. (2023). Striving for the United Nations (UN) sustainable development goals (SDGs) in BRICS economies: The role of green finance, fintech, and natural resource rent. *Sustainable Development*, 31(5), 3657-3672.
- Xu, J., Zhao, J., She, S., & Liu, W. (2022). Green growth, natural resources and sustainable development: evidence from BRICS economies. *Resources Policy*, 79, 103032.
- Hassan, A., Yang, J., Usman, A., Bilal, A., & Ullah, S. (2023). Green growth as a determinant of ecological footprint: do ICT diffusion, environmental innovation, and natural resources matter?. *PLoS One*, 18(9), e0287715.
- Han, F., Mao, X., Yu, X., & Yang, L. (2024). Government environmental protection subsidies and corporate green innovation: Evidence from Chinese microenterprises. *Journal of Innovation & Knowledge*, 9(1), 100458.

- Dey, P., Mahapatra, B. S., Mitra, B., Sarvadamana, A. K., Chowdhury, A. R., Rana, A., & Mandal, D. (2024). Potential nexus approach for sustainable soil productivity resource management. In *Environmental nexus for resource management* (pp. 243-273). CRC Press.
- Kálmán, B. G., Vasa, L., & Malatyinszki, S. (2025). Sustainable economic goals based on determinants of resource productivity in The Netherlands and Hungary. *Environmental Economics*, 16(1), 114-128.
- Afolabi, J. A. (2025). Towards carbon neutrality in Europe: The role of technology exports, renewable energy consumption, and resource productivity. *Journal of environmental management*, 395, 127862.
- Yao, C., & Xi, B. (2023). Does environmental protection tax improve green total factor productivity? Experimental evidence from China. *Environmental Science and Pollution Research*, 30(48), 105353-105373.
- Blomsma, F., & Brennan, G. (2017). The emergence of circular economy: a new framing around prolonging resource productivity. *Journal of industrial ecology*, 21(3), 603-614.
- Adebayo, T. S., Meo, M. S., Eweade, B. S., & Özkan, O. (2024). Analyzing the effects of solar energy innovations, digitalization, and economic globalization on environmental quality in the United States: TS Adebayo et al. *Clean Technologies and Environmental Policy*, 26(12), 4157-4176.