recycling

MDPI

Article

Environmental Effects of Bio-Waste Recycling on Industrial Circular Economy and Eco-Sustainability

Sasmoko [1], Khalid Zaman [2,*], Maida Malik [3], Usama Awan [4,*], Wiwik Handayani [5], Mohd Khata Jabor [6] and Muhammad Asif [7]

1 Primary Teacher Education Department, Faculty of Humanities, Bina Nusantara University, Jakarta 11480, Indonesia
2 Department of Economics, The University of Haripur, Haripur Khyber Pakhtunkhwa, Haripur 22060, Pakistan
3 Department of Management Sciences, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan
4 Sustainability Center for Research on Digitalization & Sustainability, Inland Norway Business School, Inland Norway University of Applied Sciences, Strandvegen 3, 2212 Kongsvinger, Norway
5 Faculty of Business and Economics, Universitas Pembangunan Nasional (UPN), Veteran Jawa Timur, Surabaya 60294, Indonesia
6 Faculty of Social Sciences & Humanities, Universiti Teknologi Malaysia (UTM), Skudai 81310, Johor, Malaysia
7 Department of Business Administration, Multan Campus, Air University, Multan 60650, Pakistan
* Correspondence: khalid_zaman786@yahoo.com or khalid.zaman@uoh.edu.pk (K.Z.); awan.usama@gmail.com (U.A.)

Abstract: Few prior studies have examined the social and environmental consequences of waste generation and recycling, resulting in a policy gap in the sustainability agenda. The research filled a knowledge vacuum in the literature by investigating the environmental repercussions of different waste generation and recycling processes in the Chinese economy. The study analyzed waste production and recycling statistics over the last 46 years, from 1975 to 2020, and their impact on the nation's emissions per capita. This study used four primary approaches to determine the links between the examined variables, beginning with the unit root test, which identifies the stationary process of the variables' underlying processes. Second, the autoregressive distributed lag (ARDL) model was used to produce the variables' short- and long-run estimates. Third, estimations of Granger causality examined the causal relationships between the variables. Finally, innovation accounting matrices (IAM)were utilized to predict the relationships between variables during the following decade. The unit root estimates imply the mix order of variable integration; hence, it is appropriate to employ ARDL modeling for parameter estimations. The ARDL estimations demonstrate that combustible renewables and waste decrease a nation's carbon emissions by boosting industrial waste recycling. Despite recycling systems, carbon emissions have escalated to uncontrolled levels owing to the massive production of municipal solid garbage. Sustainable waste management and recycling are vital to reducing carbon emissions. Granger's estimations of causation imply that combustible renewables and waste and carbon emissions cause industrial and municipal solid waste recycling. Additionally, population growth is responsible for greenhouse gas emissions, biowaste recycling, and industrial waste recycling. Furthermore, this shows the two-way connections between combustible renewables and waste and carbon emissions, implying the need to develop green waste recycling strategies in a nation. The IAM method identified future relationships between variables, which aids policymakers in implementing sustainable waste management practices for a nation. This study concludes that the environmental consequences of waste generation and recycling impede the nation's circular economy agenda, which can be sustained by knowledge spillovers, chemical reduction in manufacturing, and allocating a certain amount of US dollars to ecological resource conservation.

Keywords: waste generation; biowaste recycling; circular economy; municipal solid waste recycling; population growth; China

Citation: Sasmoko; Zaman, K.; Malik, M.; Awan, U.; Handayani, W.; Jabor, M.K.; Asif, M. Environmental Effects of Bio-Waste Recycling on Industrial Circular Economy and Eco-Sustainability. *Recycling* **2022**, *7*, 60. https://doi.org/10.3390/recycling7040060

Academic Editor: Elena Rada

Received: 11 June 2022
Accepted: 12 August 2022
Published: 15 August 2022

1. Introduction

Waste management is a critical concern that negatively impacts sustainable healthcare and decreases environmental quality. Additionally, it increases the burden of accomplishing a green and clean development goal, as the United Nations has extensively urged governments to react effectively via responsible production and consumption behavior [1,2]. The stated aim is reflected in the United Nations' sustainable development target 12 (SDG 12), which emphasizes the need for recycling to address the economy's healthcare challenges. Additionally, the recycling process raises the problem of sustainability [3,4]. Governments must address waste as a significant factor in the climate crisis. Recycling is one of these successful waste management solutions. The latest recycling technology should be considered while recycling since recycling is also connected to the planet's atmosphere [5,6]. The process of methanogenesis, which is used to recycle biowaste, results in the production of biogas, which is analogous to the emissions produced by burial. Treatment facilities compost organic material. The term "compost" refers to an organic fertilizer that may be used in agriculture and horticulture. Composting made from non-organic materials such as paper, glass, plastics, and metals does not benefit from the addition of organic matter. The structure of the soil, its fertility, and the amount of organic matter that is lacking may all be improved by compost. Recycling organic waste helps reduce emissions of greenhouse gases such as methane and carbon dioxide, which contribute to global warming. The Sustainable Development Goal 11 (sustainable cities and communities) focuses on cities' negative environmental impacts per capita, including pollution levels and municipal and other trash collection challenges. SDG 12 requires a reduction in food waste and prevention of waste. The Paris Agreement empowers states to include waste management in their Nationally Determined Contributions to mitigate global warming [7]. Recycling and waste management are critical government services for the environment and public health. Effective recyclable services are critical for urban designers and managers, the sustainability and health of economies, and the enjoyment of public space. When urban waste management services and systems fail, citizens suffer, especially in poorer neighborhoods and slums, and social discontent increases. As urbanization and consumerism spread, waste has evolved from an inevitable result of industrialized nations to a desirable reusable resource. This transformation is shown by the growing worldwide awareness and interest in the "circular economy" [8]. China is transforming its decarbonization strategy from linear to circular. Therefore, it may profit from the waste management techniques and analyses of other nations to assist in developing eco-friendly cities [9]. China has begun implementing transformation programs to mitigate the adverse impacts of carbon consumption. Concerns over using carbon resources for electricity and transportation have moved China to the forefront of bioenergy and intelligent uses, including hybrid cars. The transition to a circular carbon economy, on the other hand, has been gradual [10].

In 2020, the new Solid Waste Law will take effect. China has strengthened government monitoring and management responsibilities and implemented waste avoidance measures. This emphasizes compliance and item ownership [11]. By 2025, the country has established a target of repurposing more than 50% of urban household waste. China is the second-biggest producer of MSW in the world. Shanghai was one of 46 major cities in which the federal government announced intentions to recycle 35% of waste by 2020. In July, the city became the first in China to require rubbish sorting [12]. Table 1 summarizes the country's waste management profile based on the authors' suggestions for trash recycling in China.

Table 1. Trend Analysis of Carbon Emissions, Waste Generation, and Recycling(1975–2020) in China.

Years	CO_2 (Metric Tons per Capita)	Combustible Renewables and Waste (% of Energy Use)	Biowaste Recycling [a] (% of GNI)	Industry Waste Recycling [a] (% of Manufacturing Value Added)	Municipal Solid Waste Recycling [a] (USD)
1975	1.250	34.763	0.400	5.672	253.008
1985	1.871	27.270	0.425	5.024	500.346
1995	2.560	19.444	0.425	5.703	1140.02
2005	4.463	8.983	0.447	5.494	2543.03
2015	7.124	2.883	0.447	5.405	6012.32
2020	7.352	2.883	0.447	5.405	7777.77

Source: World Bank [13] and authors estimates. Note: [a] shows authors estimates.

China's carbon emissions per capita significantly increased from 1.250 in 1975, progressively increasing every decade to date. Carbon emissions dramatically increased from 4.463 metric tonnes per capita in 2005 to 7.124 metric tonnes in 2015 and then progressively increased to 7.352 metric tonnes in 2020. On the other hand, the nation significantly reduced its reliance on combustible renewables and waste, from 34.763 percent in 1975 to 19.444 percent in 1995, and then steadily lowered to 2.883 percent in 2020. The research employed knowledge spillover (a surrogate for education expenditures) to calculate biowaste recycling, which was supposed to be one-fourth of combustible renewables and waste (CRW) multiplied by the biowaste production relative to CRW. Using knowledge spillover as an interacting component in biowaste formation determines the amount of knowledge necessary to recycle biowaste in terms of GNI. According to the projections, biowaste recycling needed 0.400 percent of GNI in 1975, which increased to 0.477 percent over the last three decades. Similarly, industrial waste recycling and municipal solid waste recycling are suggested by excluding chemicals used in manufacturing value-added and appropriate waste finance in US dollars compared to combustible renewables and trash. By 2020, industrial waste recycling will be expected to reduce chemical consumption in manufacturing processes by 5.405 percent. Finally, approximately USD7777.77 per capita recycling of municipal solid trash is needed by 2020. The entire concept of recycling is discussed in further detail later in the article. Numerous previous research examined the effects of combustible renewable and waste (CRW) on environmental quality and economic development, concluding that CRW which negatively influences the country's economic growth and air quality indices [14]. Additionally, asymmetries exist between clean energy development and ecological indicators, and it was shown that non-renewable energy sources degrade environmental quality. In contrast, clean and green energy sources are critical for progressing toward sustainable development [15]. Sectoral ecological indicators are favorably related to using sustainable energy sources in transportation, residential development, and public services [16]. Technological innovation gives an alternate path to sustainable economic and environmental resources [17]. Fossil fuel burning generates additional GHG emissions, which must be offset by biomass production [18]. Ecological balance is necessary to maintain a healthy relationship between biotic resources and the physical environment, enabling sustainable waste management [19]. The research developed the following hypothesis based on the mentioned literature.

H1: *Combustible Renewable Energy Sources and Waste Generation Have Likely Had a Detrimental Influence on Environmental Quality.*

The environmental consequences of recycling, reusing, and recovering have significant policy implications for using artificial intelligence networking [20]. Product design is critical for minimizing waste formation, avoiding health risks, and reducing hazardous chemicals generated by the e-waste [21]. The COVID-19 epidemic has had a detrimental impact on hospital solid waste management, increasing waste disposal. Virus transmission risk is also minimized via solid waste management procedures that assist patients in developing a robust immune system and transitioning to balanced meals without jeopardizing their health due to garbage mismanagement [22]. The textile industry wastewater and treatment are still required to advance the sustainability goal in healthcare [23]. Anaerobic digestion employing organic waste as a substrate assists in mitigating worries about GHG emissions [24]. Because plastics have significantly improved our quality of life, it is vital to transition to sustainable alternatives such as bio-based plastics [25]. The second hypothesis of our research is as follows, based on the relevant literature:

H2: *Adequate Waste Recycling Processes Are Expected to Reduce Environmental Costs.*

Massive population expansion and urbanization tend to raise healthcare risks related to increased solid waste output, which results in increased GHG emissions. Converting garbage into energy is critical for accomplishing the sustainable development goal [26]. Thermal and biological waste management techniques are used from waste to energy and energy to waste. Thermal waste-to-energy processes include the pyrolysis process, decomposition, and cremation. It is used to create electricity in internal combustion engines and turbines. Additionally, biomethanation optimizes biogas for energy generation [27]. Almost half of the collected MSW is publicly burnt or disposed of in landfills in most developing nations. The remainder is gathered and processed. Waste management is responsible for approximately 5% of total GHG emissions into the environment. Methane production contributes to between 1% and 2% of total GHG emissions. Ecological efficiency is critical for resource conservation and environmental protection throughout the collection, processing, and disposal processes [28]. Incineration offers better potential for reducing GHG emissions than gasification or anaerobic digestion since it can process a bigger volume of waste and generate more energy [29]. By tightening restrictions and implementing the provided waste reduction route, MSW disposal at the designated garbage landfill may be decreased [30]. The debt-to-income ratio promotes MSW growth, but the debt-to-output ratio restrains it. Thus, the debt-to-income ratio should be used to promote economic development in conjunction with a reduction in MSW production and an improvement in ecological standards [31]. The third hypothesis of the investigation is as follows:

H3: *Population Expansion Tends to Increase Solid Waste Output, Which Is Likely to Negatively Influence Natural Resources.*

The research contributes the following to previous studies that addressed the following gaps in the literature, i.e.,

(i) Earlier research primarily focused on industrial waste and its recycling influence on the environment or municipal solid waste and its recycling [32,33].The composite modeling technique is used to evaluate the stated concern. The current research evaluated three distinct waste streams (biowaste, industrial waste, and municipal solid waste) and their recycling procedures to determine their environmental impact on the Chinese economy.

(ii) Previous studies directly assessed the environmental impacts of garbage recycling but could not quantify the costs involved with recycling procedures [34–36]. In prior iterations of the above described issue, the additive compliance technique was used. This study evaluated three distinct socioeconomic and environmental costs associated with recycling the stated wastes for the Chinese economy, including the knowledge spillover cost as a percentage of GNI, the percentage reduction in the chemicals used in manufacturing value-added, and the amount of income required to dispose of and recycle municipal waste.

(iii) The study used population growth as a control variable in the pollution damage function via the IPAT principle. The control variable in the research that quantifies human footprints on arable land degrades environmental quality through trash creation. Earlier studies extensively employed the IPAT hypothesis in various economic settings, by using a variety of approaches to statistical analysis of time series [37–39]. However, it was confined to the waste production and recycling processes evaluated in this research to develop sound policies.

The following research issues must be addressed in light of the extensive debate. First, do combustible renewables and garbage contribute more to a country's environmental degradation? Increased biowaste, industrial effluent, and municipal solid waste all contribute to increased health risks due to increased carbon emissions. As a result, recycling trash is critical for environmental quality improvement. Second, to which channel would it be beneficial to recycle the garbage to minimize carbon emissions? The increased demand for environmental awareness among the population through information spillovers would aid in the reduction in biowaste. Additionally, carbon emissions may be lowered via industrial waste recycling by reducing the chemicals used in the production process. A rise in the country's per capita income would enable it to spend more money on municipal solid waste reduction, which contributes to reducing health dangers via the trash recycling process. Finally, does rapid population expansion put more strain on arable land, resulting in increased environmental harm to a country? The critical requirement for urban city planning is critical for rural populations to be absorbed into metropolitan areas in order to maintain natural resources. The following study goals have been established for assessing the environmental consequences of waste creation and recycling in the Chinese economy:

(i) To determine the effect of combustible renewables and waste generation on a country's carbon emissions;
(ii) To examine the impacts of biowaste recycling, industrial waste recycling, and municipal solid waste recycling on environmental quality;
(iii) To analyze the influence of population expansion on ecological degradation in a nation.

The stated research objectives were evaluated using empirical statistical techniques, such as time series cointegration, the Granger causality test, and the innovation accounting matrix to gain insight into parameter estimates, cause–effect relationships, and forecast relationships between variables.

2. Data Source and Methodology

2.1. List of Variables and Measurement

The aggregated data of the combustible renewables and waste (denoted by *CRW*) is accessible in the World Bank database [13] as a percentage of total energy usage. It comprises solid and liquid biomass, biogas, industrial effluent, and municipal trash. The research divided the indicated waste into three primary groups giving specified weights to them. For instance, the weight of solid and liquid biomass and biogas waste (denoted by *BIOW*) is one-fourth of the total energy consumption. Industrial waste (*INDW*) accounts for fifty percent of total energy use. In contrast, municipal solid waste (*MSW*) accounts for three-quarters of overall energy use. The given weight of the mentioned wastes helps calculate recycling costs for a nation. Equation (1) illustrates the weighted components of distinct solid wastes that are employed in this research, i.e.,

$$CRW = \frac{1}{4}(BIOW) + \frac{2}{4}(INDW) + \frac{3}{4}(MSW) \quad (1)$$

Additionally, the research analyzed education expenditures (as a percentage of GNI), chemicals used (as a percentage of manufacturing value added), and GDP per capita (in constant 2015 USD) to estimate the solid waste recycling for specific proposals. First, it is anticipated that the greater the information spillover is, the better the awareness of the general public is with regard to decreasing biowaste creation, and thus that its interaction with waste generation would provide precise predictions of biowaste recycling as a proportion of total gross national revenue. Equation (2) illustrates the process of calculating biowaste recycling (abbreviated *BIOWRECY*), i.e.,

$$BIOWRECY = \frac{\sum (BIOW \times EDUEXP)}{\sum CRW} = \text{\% of GNI} \quad (2)$$

Second, it is presumed that the more chemicals are used in manufacturing value-added, the more industrial waste is generated. Thus, the interaction terms for both factors about total combustible renewables waste would indicate the percentage of manufacturing value-added that would likely be required to transition to industrial waste recycling. Equation (3) illustrates the computation for industrial waste recycling (designated by the abbreviation *INDWRECY*), i.e.,

$$INDWRECY = \frac{\sum (INDW \times CHEM)}{\sum CRW} \quad (3)$$

Finally, it is clear that solid waste management requires a greater financial investment in order to properly dispose of rubbish and maintain a sufficient budget for recycling. As a result, the research employed the interaction term of a country's GDP per capita and municipal solid waste as a percentage of total combustible renewables waste to calculate the per capita income necessary to recycle municipal waste effectively (designated by *MSWRECY*). Equation (4) illustrates the computation, i.e.,

$$MSWRECY = \frac{\sum (MSW \times GDPPC)}{\sum CRW} \quad (4)$$

Additionally, the research employed yearly percentage population growth (referred to as POPG) as a controlled variable. The study's response variable is carbon dioxide emissions in metric tonnes per capita (denoted by CO_2). The data were extracted from the World Bank's database [13].

2.2. Theoretical Framework

The waste management theory encompasses all facets of waste management, including conceptual assessments, recycling behavior, and waste disposal objectives. According to waste management theory, waste management prevents environmental contamination, which is crucial for long-term waste management. The regulation mainly focuses on waste [40]. On the other hand, recycling is a vital enabler of the transition from a linear to a circular economy [41]. Due to the potential benefits of a circular economy, specialists focus on developing methods to encourage circular economy activities [42]. Circular economy refers to Alhawari et al. [43] "the set of organizational planning processes for creating, delivering products, components, and materials at their highest utility for customers and society through effective and efficient utilization of ecosystem, economic, and product cycles by closing loops for all the related resource flows" (p. 13). Given the importance of remanufacturing and recycling, businesses must comprehend the skills and procedures for resource allocation that contribute to sustainability initiatives [44]. Clarifying roles and responsibilities at all levels of government is crucial for achieving low CO_2 emissions and energy savings, which will accelerate and simplify the process [45]. A few modifications to processes or products might result in significant emission reductions since approximately 85–90 percent of current greenhouse gas emissions are attributed to a few firms [46]. Prioritizing recycling in green supply chain operations paves the door for intelligent manufacturing systems [47]. Awan [48] asserts that products developed from recyclable resources will almost certainly increase economic profit. Sustainable production and consumption systems are managed and planned in a linear to closed-loop approach, resulting in long-term advantages across all sustainability aspects, including social, environmental, and economic well-being [49]. The research expanded the IPAT ((emissions intensity (I) is impacted by population growth (P), affluence (A), and technology (T) model based on the theoretical debate, i.e.,

$$I = \alpha_0 + \alpha_1 P + \alpha_2 A + \alpha_3 T + \varepsilon \quad (5)$$

It is self-evident that rapid population expansion results in increased carbon emissions due to increased solid waste; hence, significant technology to recycle garbage is essential to mitigate environmental issues. Thus, the following modification is made to Equation (6):

$$CO2 = \alpha_1 + \alpha_1 POPG + \alpha_2 CRW + \alpha_3 BIOWRECY + \alpha_3 INDWRECY + \alpha_3 MSWWRECY + \varepsilon_t \quad (6)$$

The following expected relationship is as follows:

$\frac{\partial CO2}{\partial POPG} > 0$ Higher population expansion creates more carbon emissions via a higher accumulation of solid waste;

$\frac{\partial CO2}{\partial CRW} > 0$ The increased production of biowaste, industrial waste, and municipal solid waste results in more carbon emissions;

$\frac{\partial CO2}{\partial BIOWRECY} < 0$ By increasing biowaste recycling, carbon emissions are reduced;

$\frac{\partial CO2}{\partial INDWRECY} < 0$ Recycling industrial waste contributes to environmental improvement and reduces carbon emissions;

$\frac{\partial CO2}{\partial MSWRECY} < 0$ Increased municipal solid waste management results in a reduction in carbon emissions.

2.3. Econometric Framework

The following sequential statistical techniques applied to the dataset to obtain parameter estimates, help to formulate sustainable policies, i.e.,

Step-I: Unit Root Test

First, the research used an autoregressive component to examine the time-varying stationary series of the interesting variables. The AR(1) model states that

$$y_t = \theta y_{t-1} + \varepsilon_t \quad (7)$$

where ε_t is the error term.

It is possible to determine whether a series is level stationary, explodes, becomes non-stationary, or becomes first differenced stationary in four ways:

Case 1: $|\theta| < 1$, the series is level stationary;
Case 2: $|\theta| > 1$, the series explodes;
Case 3: $|\theta| = 1$, the variable is non-stationary series;
Case 4: $y_t - y_{t-1} = \Delta y_t = \varepsilon_t$ the series is differenced stationary.

Using the following equation, the augmented Dickey–Fuller(ADF) unit root test is used to examine the integration order of the candidate variables, i.e.,

$$\begin{aligned}
\Delta CO2_t &= \alpha + \beta TIME + \gamma CO2_{t-1} + \delta_1 \Delta CO2_{t-1} + \ldots + \delta_{p-1} \Delta CO2_{t-p-1} + \varepsilon_t \\
\Delta CRW_t &= \alpha + \beta TIME + \gamma CRW_{t-1} + \delta_1 \Delta CRW_{t-1} + \ldots + \delta_{p-1} \Delta CRW_{t-p-1} + \varepsilon_t \\
\Delta BIOWRECY_t &= \alpha + \beta TIME + \gamma BIOWRECY_{t-1} + \delta_1 \Delta BIOWRECY_{t-1} + \ldots + \delta_{p-1} \Delta BIOWRECY_{t-p-1} + \varepsilon_t \\
\Delta INDWRECY_t &= \alpha + \beta TIME + \gamma INDWRECY_{t-1} + \delta_1 \Delta INDWRECY_{t-1} + \ldots + \delta_{p-1} \Delta INDWRECY_{t-p-1} + \varepsilon_t \\
\Delta MSWRECY_t &= \alpha + \beta TIME + \gamma MSWRECY_{t-1} + \delta_1 \Delta MSWRECY_{t-1} + \ldots + \delta_{p-1} \Delta MSWRECY_{t-p-1} + \varepsilon_t \\
\Delta POPG_t &= \alpha + \beta TIME + \gamma POPG_{t-1} + \delta_1 \Delta POPG_{t-1} + \ldots + \delta_{p-1} \Delta POPG_{t-p-1} + \varepsilon_t
\end{aligned} \quad (8)$$

where 'α' is a constant, 'β' is the time trend coefficient, and 'p' shows the AR lag process. The lag is determined based on the AIC method. By imposing restrictions on $\alpha = \beta = 0$, random walks with drift are generated by this equation.

Step-II: ARDL-Bounds Testing Approach

The ARDL-bounds testing approach proposed by Pesaran et al. [50] employs unit root estimation to integrate variables from order 0 and 1. The single regression equation may provide odd results if I(0) and I(1) variables are intermingled. Thus, they used difference and lag operators to solve the issue of simultaneity. However, the long-term trend of the variables is predictable for parameter estimation. During regression, the error correction term is taken into account, showing the model's convergence. Equation (9) shows the ARDL specification used to estimate the model, i.e.,

$$\begin{aligned} \ln(CO2)_t &= \alpha_0 + \sum_{i=1}^{p} \phi_i \Delta \ln(CO2)_{t-i} + \sum_{i=0}^{q} \theta_i \Delta \ln(CRW)_{t-i} + \sum_{i=0}^{r} \theta_i \Delta \ln(BIOWRECY)_{t-i} + \sum_{i=0}^{t} \varphi_i \Delta \ln(INDWRECY)_{t-i} \\ &+ \sum_{i=0}^{u} \varphi_i \Delta \ln(MSWRECY)_{t-i} + \sum_{i=0}^{w} \varphi_i \Delta \ln(POPG)_{t-i} + \delta_1 \ln(CRW)_t + \delta_2 \ln(BIOWRECY)_t + \delta_3 \ln(INDWRECY)_t \\ &+ \delta_4 \ln(MSWRECY)_t + \delta_5 \ln(POPG)_t + \varepsilon_t \end{aligned} \tag{9}$$

where Δ shows the first difference operator while p shows the optimal lag length.

After the regression, the research verified for long-run cointegration using Wald F-statistics. The Wald F-statistics are used to analyze the null and alternative hypotheses, i.e.,

H0: $\delta 1 = \delta 2 = \delta 3 = \delta 4 = \delta 5 = 0$

H1: $\delta 1 \neq \delta 2 \neq \delta 3 \neq \delta 4 \neq \delta 5 \neq 0$

The null hypothesis indicated that no cointegration exists between the variables, but the alternative hypothesis verified it. The Narayan [51] critical values are utilized to test both hypotheses. Regression analysis validated the model's convergence towards equilibrium at a predetermined rate of model modification, i.e.,

$$\begin{aligned} \ln(CO2)_t &= \alpha_0 + \sum_{i=1}^{p} \phi_i \Delta \ln(CO2)_{t-i} + \sum_{i=0}^{q} \theta_i \Delta \ln(CRW)_{t-i} + \sum_{i=0}^{r} \theta_i \Delta \ln(BIOWRECY)_{t-i} + \sum_{i=0}^{t} \varphi_i \Delta \ln(INDWRECY)_{t-i} \\ &+ \sum_{i=0}^{u} \varphi_i \Delta \ln(MSWRECY)_{t-i} + \sum_{i=0}^{w} \varphi_i \Delta \ln(POPG)_{t-i} + \delta_1 \ln(CRW)_t + \delta_2 \ln(BIOWRECY)_t + \delta_3 \ln(INDWRECY)_t \\ &+ \delta_4 \ln(MSWRECY)_t + \delta_5 \ln(POPG)_t + \lambda ECT_{t-1} + \varepsilon_t \end{aligned} \tag{10}$$

where ECT_{t-1} shows the error correction term and the model's adjustment parameter.

Step-III: Granger Causality

The Granger causality test was then used to the selected variables to assess their causality. The F-test is used to determine whether the variables have one-way or two-way links or whether the relationship is neutral despite being strongly linked. These three causality inferences assist in formulating long-term growth policies. The following causal link between variables may be seen as follows:

(i) Unidirectional causality: carbon emissions Granger cause combustible waste, biowaste recycling, industrial waste recycling, and municipal solid waste recycling but not vice versa;
(ii) Reverse causality: combustible waste, biowaste recycling, industrial waste recycling, and municipal solid waste recycling Granger cause carbon emissions but not vice versa;
(iii) Bidirectional causality: the variables have a two-way linkage between them;
(iv) Neutrality: the variables do not confirm any causality pattern between the variables.

For Granger causality, the VAR framework (Equation (11)) is used, i.e.,

$$
\begin{bmatrix} \ln(CO2)_t \\ \ln(CRW)_t \\ \ln(BIOWRECY)_t \\ \ln(INDWRECY)_t \\ \ln(MSWRECY)_t \\ \ln(POPG)_t \end{bmatrix} = \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \sigma_{11t}\sigma_{12t}\sigma_{13t}\sigma_{14t}\sigma_{15t} \\ \sigma_{21t}\sigma_{22t}\sigma_{23t}\sigma_{24t}\sigma_{25t} \\ \sigma_{31t}\sigma_{32t}\sigma_{33t}\sigma_{34t}\sigma_{35t} \\ \sigma_{41t}\sigma_{42t}\sigma_{43t}\sigma_{44t}\sigma_{45t} \\ \sigma_{51t}\sigma_{52t}\sigma_{53t}\sigma_{54t}\sigma_{55t} \\ \sigma_{61t}\sigma_{62t}\sigma_{63t}\sigma_{64t}\sigma_{65t} \end{bmatrix} \times \begin{bmatrix} \ln(CO2)_{t-1} \\ \ln(CRW)_{t-1} \\ \ln(BIOWRECY)_{t-1} \\ \ln(INDWRECY)_{t-1} \\ \ln(MSWRECY)_{t-1} \\ \ln(POPG)_{t-1} \end{bmatrix} + \sum_{j=p+1}^{d\max} \begin{bmatrix} \theta_{11j}\theta_{12j}\theta_{13j}\theta_{14j}\theta_{15j} \\ \theta_{21j}\theta_{22j}\theta_{23j}\theta_{24j}\theta_{25j} \\ \theta_{31j}\theta_{32j}\theta_{33j}\theta_{34j}\theta_{35j} \\ \theta_{41j}\theta_{42j}\theta_{43j}\theta_{44j}\theta_{45j} \\ \theta_{51j}\theta_{52j}\theta_{53j}\theta_{54j}\theta_{55j} \\ \theta_{61j}\theta_{62j}\theta_{63j}\theta_{64j}\theta_{65j} \end{bmatrix} \times \begin{bmatrix} \ln(CO2)_{t-j} \\ \ln(CRW)_{t-j} \\ \ln(BIOWRECY)_{t-j} \\ \ln(INDWRECY)_{t-j} \\ \ln(MSWRECY)_{t-j} \\ \ln(POPG)_{t-j} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \tag{11}
$$

Equation (12) shows Granger causality for the multivariate system, i.e.,

$$
\begin{aligned}
CO2_t &= c_1 + \sum_{i=1}^{2} \beta_1 CO2_{t-i} + \sum_{i=1}^{2} \beta_2 CRW_{t-i} + \sum_{i=1}^{2} \beta_3 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_4 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_5 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_6 POPG_{t-i} + \varepsilon \\
CRW_t &= c_1 + \sum_{i=1}^{2} \beta_1 CRW_{t-i} + \sum_{i=1}^{2} \beta_2 CO2_{t-i} + \sum_{i=1}^{2} \beta_3 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_4 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_5 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_6 POPG_{t-i} + \varepsilon \\
BIOWRECY_t &= c_1 + \sum_{i=1}^{2} \beta_1 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_2 CRW_{t-i} + \sum_{i=1}^{2} \beta_3 CO2_{t-i} + \sum_{i=1}^{2} \beta_4 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_5 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_6 POPG_{t-i} + \varepsilon \\
INDWRECY_t &= c_1 + \sum_{i=1}^{2} \beta_1 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_2 CRW_{t-i} + \sum_{i=1}^{2} \beta_3 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_4 CO2_{t-i} + \sum_{i=1}^{2} \beta_5 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_6 POPG_{t-i} + \varepsilon \\
MSWRECY_t &= c_1 + \sum_{i=1}^{2} \beta_1 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_2 CRW_{t-i} + \sum_{i=1}^{2} \beta_3 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_4 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_5 CO2_{t-i} + \sum_{i=1}^{2} \beta_6 POPG_{t-i} + \varepsilon \\
POPG_t &= c_1 + \sum_{i=1}^{2} \beta_1 POPG_{t-i} + \sum_{i=1}^{2} \beta_2 CRW_{t-i} + \sum_{i=1}^{2} \beta_3 BIOWRECY_{t-i} + \sum_{i=1}^{2} \beta_4 INDWRECY_{t-i} + \sum_{i=1}^{2} \beta_5 MSWRECY_{t-i} + \sum_{i=1}^{2} \beta_6 CO2_{t-i} + \varepsilon
\end{aligned} \tag{12}
$$

The null and alternative hypothesis is as follows:

H0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$

HA: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq 0$

Acceptance of the null hypothesis revealed no causal link between the variable and the dependent variable, whereas the rejection of the null hypothesis confirmed a causal relationship. As such, the model can estimate predicted associations between variables.

Step-IV: Impulse Response Function (IRF) and Variance Decomposition Analysis (VDA)

To sum up, the IRF measures how much a predictor influences a response variable, whereas VDA measures the connection between variables across time. It estimates how much of the variation in each variable's prediction inaccuracy may be explained by exogenous shocks. Using the VAR(p) form, the forecast error variance may be computed.

$$
y_t = v + \alpha_1 y_{t-1} + \ldots + \alpha_p y_{t-p} + \varepsilon_t \tag{13}
$$

Equation (12) transformed into a VDA operator, i.e.,

$$\begin{aligned} &Var(\sigma(Y, X) = Var(E[\sigma \perp X]) + E[Var(\sigma \perp X)] \\ &\Rightarrow Var(E[\sigma \perp X]) \leq Var(\sigma[Y, X)] \end{aligned} \tag{14}$$

Equation (14) shows the mean square error term for the group of exogenous variables, i.e.,

$$\begin{aligned} MSE_{\mu} &= E_{CRW}[MSE_{\mu}(CRW)] \\ MSE_{\mu} &= E_{BIOWRECY}[MSE_{\mu}(BIOWRECY)] \\ MSE_{\mu} &= E_{INDWRECY}[MSE_{\mu}(INDWRECY)] \\ MSE_{\mu} &= E_{MSWRECY}[MSE_{\mu}(MSWRECY)] \\ MSE_{\mu} &= E_{POPG}[MSE_{\mu}(POPG)] \end{aligned} \tag{15}$$

where MSE shows mean square error.

The forecasted period is from 2022 to 2031, which helps policymakers formulate policies. They assist in identifying the factors that have the most potential to influence the response variable over time. The inter-temporal link inspires think tanks to develop sustainable waste generation programs.

3. Results

The analysis of the dataset used a variety of estimation-based statistical methods. First, the descriptive statistics of the variables not only guided its trend analysis during the period but also allowed policymakers to conduct a comprehensive examination of the factors that influenced the response variable. The correlation matrix is an additional essential technique for obtaining a priori expectations between variables heading toward the central regression apparatus. The ADF unit root test is used for the long-term trended series dataset to determine the presence of the random walk hypothesis. The ARDL-bounds testing approach evaluates the short- and long-run elasticities between variables, which aids in developing appropriate policy interventions. The Granger causality test reveals the pattern of causation between variables, leading to long-term solutions for the economies. Lastly, the IAM method is used to performan ex-ante analysis between variables over the ten following years. The changes in the method and data help to recommend future sustainability decisions for the country.

The variables' descriptive statistics are shown in Table 2. Carbon emissions range from 1.250 metric tonnes per capita to 7.352 metric tonnes per capita, with an average of 3.656 metric tonnes per capita. The standard deviation is 2.239 metric tonnes per capita, and the distribution is positively skewed with a kurtosis of 1.772. The average value of combustible renewables and waste is 17.043 percent of energy usage, with a maximum value of 34.763 percent of energy use. The standard deviation is more than one, implying that 1.740 percent of energy consumption may be added to the maximum amount of waste. The findings demonstrate a negatively skewed distribution, with the distribution's peak being much lower than the carbon emissions amount. On average, 0.439 percent of gross national income is needed to recycle biowaste, with a maximum of 0.508 percent. The standard deviation is 0.025 percent of GNI, with a negatively skewed distribution. Compared to other waste recycling, its distribution peak is bigger than that of industrial waste recycling and municipal waste recycling. Recycling industrial waste requires an average of 5.608 percent of manufacturing value-added, with a maximum of 6.553 percent and a minimum of 4.887 percent. The standard deviation for waste recycling is 0.338 percent of industrial value-added. The average cost of recycling municipal solid waste is USD2376.166 per capita, with a maximum cost of USD7777.769 and a lowest cost of USD245.211. The greater standard deviation value near their average value demonstrates the wide variability in municipal solid waste recycling and indicates that more funds are required to recycle wastes. The yearly average percentage of a population increase is 0.976, ranging from 1.766 to 0.225. Compared to combustible renewables and waste, the standard deviation is 0.421 percent, indicating a favorably skewed distribution and a larger height of observations. The trend analysis advises proceeding in the direction of correlation between the provided variables to arrive at some convincing findings.

Table 2. Descriptive statistics.

Methods	CO_2	CRW	BIOWRECY	INDWRECY	MSWRECY	POPG
Mean	3.656	17.043	0.439	5.608	2376.166	0.976
Maximum	7.352	34.763	0.508	6.553	7777.769	1.766
Minimum	1.250	2.883	0.375	4.887	245.211	0.225
Std. Dev.	2.239	10.740	0.025	0.338	2330.926	0.421
Skewness	0.661	−0.055	−0.273	0.396	1.015	0.104
Kurtosis	1.772	1.560	4.874	3.576	2.699	1.618

Source: author's estimation.

The correlation matrix estimates in Table 3 indicate a negative correlation between combustible renewables and waste and carbon emissions, with a correlation coefficient of r = −0.952, $p < 0.000$, implying that waste generation is significantly reduced through a chemical reduction in the manufacturing process, which contributes to environmental quality improvement. This conclusion is supported by the negative connection between industrial waste recycling and carbon emissions (r = −0.445, $p < 0.001$). Biowaste and municipal solid waste recycling were positively associated with carbon emissions, indicating that both processes needed additional knowledge spillovers and US dollars to achieve the carbon reduction goals. The negative association between municipal solid waste recycling and waste creation indicates that, although MSW recycling reduces the total waste output, its influence on environmental quality continues to deteriorate due to increased R&D investments and adequate finance. MSW recycling is connected with biowaste recycling, but industrial waste recycling is adversely correlated. Thus, it is clear that MSW recycling and biowaste recycling are complementary goods that have infused knowledge spillovers with the necessary financing for environmental quality improvement. Population growth and carbon emissions are negatively correlated to support the population ingenuity idea. population ingenuity concept.

Table 3. Correlation Matrix.

Variables	CO_2	CRW	BIOWRECY	INDWRECY	MSWRECY	POPG
CO_2	1					
CRW	−0.952 (0.000)	1				
BIOWRECY	0.2715 (0.067)	−0.329 (0.025)	1			
INDWRECY	−0.445 (0.001)	0.400 (0.005)	−0.051 (0.732)	1		
MSWRECY	0.971 (0.000)	−0.905 (0.000)	0.267 (0.072)	−0.407 (0.005)	1	
POPG	−0.854 (0.000)	0.932 (0.000)	−0.407 (0.004)	0.422 (0.003)	−0.831 (0.000)	1

Source: author's estimation. Small bracket shows probability value.

According to Table 4, industrial waste recycling, MSW recycling and population growth are level static variables. The remaining variables, such as carbon emissions, CRW, and biowaste recycling, display the first differenced stationary series. Carbon emissions, waste production, and biowaste recycling show significant fluctuations between their series resulting in non-stationary values at the level; hence, their first differenced series becomes stationary. On the other hand, MSW recycling, industrial waste recycling, and population increase display a smooth pattern over time, resulting in a stationary series at the level. For the detrended series at the level, the order of integration is changed to I(1) for the variable carbon emissions, CRW, and biowaste recycling. On the other hand, for smooth data series, the order of integration is adjusted to I(0) for the variables' industrial waste recycling, MSW recycling, and population increase. The mixture of I(0) and I(1) series provides strong justification for parameter estimation using the autoregressive distributed lag (ARDL) model.

Table 4. ADF Unit Root Estimates.

Variables	Level		First Difference		Decision
	Constant	Constant and Trend	Constant	Constant and Trend	
CO_2	−0.236 (0.925)	−1.927 (0.623)	−2.919 (0.051)	−2.904 (0.170)	I(1)
CRW	−1.213 (0.660)	−1.918 (0.627)	−3.866 (0.004)	−3.969 (0.017)	I(1)
BIOWRECY	−2.516 (0.118)	−2.579 (0.291)	−9.558 (0.000)	−9.459 (0.000)	I(1)
INDWRECY	−4.659 (0.000)	−5.377 (0.000)	−6.358 (0.000)	−5.137 (0.000)	I(0)
MSWRECY	−3.158 (0.030)	−3.294 (0.082)	−1.577 (0.483)	−1.738 (0.712)	I(0)
POPG	0.108 (0.962)	−4.122 (0.012)	−2.303 (0.176)	−2.264 (0.422)	I(0)

Source: author's estimation.

Before estimating parameters using the ARDL bounds testing method, it is necessary to have an appropriate lag in the regression. The requirements for VAR lag order are shown in Table 5. The research employed AIC lag selection criteria to estimate parameters, demonstrating that up to two lags may be applied. Thus, the study took two lags into account for both the regressors and the regressand to provide unbiased and consistent results.

Table 5. Lag Length Selection.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−414.5667	NA	12.60419	19.56124	19.80699	19.65187
1	−44.32879	619.9332	2.27×10^{-6}	4.015293	5.735535 *	4.649665 *
2	−4.976833	54.90971 *	2.15×10^{-6} *	3.859388 *	7.054123	5.037507
3	29.15022	38.09531	3.09×10^{-6}	3.946502	8.615730	5.668369

Note: * indicates the lag order selected by the criterion. LR: sequential modified LR test statistic (each test at 5% level). FPE: final prediction error. AIC: Akaike information criterion. SC: Schwarz information criterion. HQ: Hannan–Quinn information criterion.

The ARDL short- and long-run estimations in Table 6 indicate a negative association between the combustible waste and carbon emissions, with elasticity values of −0.491 percent, $p < 0.001$, and −0.342 percent, $p < 0.000$, respectively. Consequently, waste generating processes are sustainable when handled via industrial waste recycling, as this significantly reduces carbon emissions in both the short and long term. According to the elasticity calculations, a 1% increase in industrial waste recycling reduces carbon emissions by −0.262 percent in the short run and −0.731 percent in the long run. The positive link between MSW recycling and carbon emissions was shown to increase carbon emissions by 0.692 percentage points in the short term and by 0.222 percent in the long run.

Table 6. ARDL short- and long-run estimates.

Dependent Variable: $\ln(CO_2)$				
Selected Model: ARDL(1, 2, 2, 2, 1, 0)				
Cointegrating Form				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$\Delta\ln(CRW)_t$	−0.491513	0.141634	−3.470298	0.0016
$\Delta\ln(CRW)_{t-1}$	−0.191393	0.149488	−1.280326	0.2102
$\Delta\ln(BIOWRECY)_t$	−0.070006	0.093683	−0.747266	0.4607
$\Delta\ln(BIOWRECY)_{t-1}$	0.161991	0.091032	1.779498	0.0853
$\Delta\ln(INDWRECY)_t$	−0.262395	0.135983	−1.929621	0.0632
$\Delta\ln(INDWRECY)_{t-1}$	0.237169	0.118494	2.001532	0.0545
$\Delta\ln(MSWRECY)_t$	0.692582	0.229318	3.020184	0.0051
$\Delta\ln(POPG)_t$	−0.011987	0.025222	−0.475269	0.6380
CointEq(−1)	−0.437703	0.098436	−4.446555	0.0001
Long Run Coefficients				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
ln(CRW)t	−0.342428	0.042306	−8.094079	0.0000
$\ln(BIOWRECY)_t$	−0.312008	0.291055	−1.071991	0.2923
$\ln(INDWRECY)_t$	−0.731784	0.331594	−2.206870	0.0351
$\ln(MSWRECY)_t$	0.222953	0.037344	5.970189	0.0000
$\ln(POPG)_t$	−0.027386	0.059682	−0.458870	0.6496
Constant	1.249614	0.652629	1.914740	0.0651

Source: author's estimation.

The ARDL bounds estimates in Table 7 demonstrate that the variables are cointegrated and have long-run correlations. The F-statistics are significant at the 1% level and fall under the I(1) upper limit, allowing for causal inferences and intertemporal correlations between the variables.

Table 7. ARDL Bounds Testing Estimates.

Test Statistic	**Value**	**k**
F-statistic	5.010604	5
Critical Value Bounds		
Significance	I(0) Bound	I(1) Bound
10%	2.26	3.35
5%	2.62	3.79
2.5%	2.96	4.18
1%	3.41	4.68

Source: author's estimates.

The diagnostic estimations in Table 8 demonstrate that the residual is regularly distributed. There are no issues with autocorrelation and heteroskedasticity in the given model. The outcome of the Ramsey RESET test shows that the presented model does not include any misspecification errors. As a result, the ARDL bounds test produces unbiased and consistent estimates.

The Granger causality estimates in Table 9 indicate a bidirectional causal relationship between combustible waste and carbon emissions, implying that waste generation processes are inextricably linked to environmental quality via two-way linkages, highlighting the importance of developing sustainable waste management policies to help the country transition to sustainable production and consumption. Additionally, carbon emissions Granger cause industrial waste recycling, confirming a country's emissions-driven industrial recycling. Population growth Granger causes carbon emissions, bio waste, and industrial waste recycling. Combustible waste contributes to industrial waste and MSW recycling in a country, substantiating the waste-driven recycling hypothesis. According to the mentioned causation findings, effective waste recycling is critical for a country's green and clean sustainable strategy.

Table 8. Diagnostic Test Estimates.

Breusch–Godfrey Serial Correlation LM Test:			
F-statistic	0.231778	Prob. F(2,28)	0.7946
Observation × R-squared	0.716582	Prob. Chi-Square(2)	0.6989
Heteroskedasticity Test: Harvey			
F-statistic	1.668845	Prob. F(13,30)	0.1208
Obs × R-squared	18.46561	Prob. Chi-Square(13)	0.1406
Scaled explained SS	16.86239	Prob. Chi-Square(13)	0.2057
Ramsey RESET Test			
Statistics	Value	df	Probability
t-statistic	0.321853	29	0.7499
F-statistic	0.103590	(1, 29)	0.7499

Source: author's estimates.

Table 9. Granger Causality Estimates.

Null Hypothesis:	**Obs**	**F-Statistic**	**Prob.**
CRW ↔ CO_2	44	4.00841	0.0261
CO_2 ↔ CRW		2.86740	0.0689
INDWRECY → CO_2	44	0.05433	0.9472
CO_2 → INDWRECY		4.88364	0.0128
POPG → CO_2	44	5.38116	0.0086
CO_2 → POPG		1.18674	0.3160
INDWRECY → CRW	44	1.53449	0.2283
CRW → INDWRECY		4.20450	0.0222
MSWRECY → CRW	44	0.68150	0.5118
CRW → MSWRECY		3.19662	0.0518
INDWRECY → BIOWRECY	44	0.54679	0.5832
BIOWRECY → INDWRECY		3.34585	0.0456
POPG → BIOWRECY	44	3.22872	0.0504
BIOWRECY → POPG		1.46776	0.2429
MSWRECY → INDWRECY	44	6.29409	0.0043
INDWRECY → MSWRECY		0.24648	0.7828
POPG → INDWRECY	44	4.93206	0.0123
INDWRECY → POPG		1.97832	0.1519

Source: author's estimation.

The IRF and VDA estimates in Table 10 indicate that sustainable waste production, biowaste recycling, and population expansion would likely reduce carbon emissions, hence supporting the sustainable waste management theory and population ingenuity principle over time. On the other hand, industrial waste and MSW recycling both need enough waste funding and knowledge spillovers to enhance their waste management practices and reduce carbon emissions over the next decade.

Table 10. IRF and VDA Estimates.

Impulse Response of CO_2						
Period	**CO_2**	**CRW**	**BIOWRECY**	**INDWRECY**	**MSWRECY**	**POPG**
2022	0.139928	0	0	0	0	0
2023	0.193110	−0.027273	−0.005942	0.008519	0.006523	0.001132
2024	0.222671	−0.044956	−0.033097	0.021223	0.002540	−0.029705
2025	0.232672	−0.060448	−0.037791	0.030220	0.007070	−0.066333
2026	0.218379	−0.081119	−0.023294	0.033915	0.014199	−0.094218
2027	0.190318	−0.105607	−0.012884	0.035860	0.016477	−0.115551
2028	0.158904	−0.128581	−0.010221	0.037161	0.015302	−0.131748
2029	0.125367	−0.147800	−0.007511	0.035309	0.013894	−0.138991
2030	0.089441	−0.163589	−0.003896	0.028371	0.012716	−0.135406
2031	0.054425	−0.175905	−0.003165	0.017025	0.011825	−0.123212
Variance Decomposition of CO_2						
Period	**CO_2**	**CRW**	**BIOWRECY**	**INDWRECY**	**MSWRECY**	**POPG**
2022	100	0	0	0	0	0
2023	98.44973	1.287644	0.061124	0.125634	0.073647	0.002219
2024	95.21380	2.472912	1.011349	0.467758	0.043821	0.790362
2025	91.04433	3.639045	1.450728	0.814252	0.056115	2.995525
2026	86.26989	5.384242	1.284651	1.071329	0.124507	5.865383
2027	80.46032	7.947887	1.075271	1.274346	0.188268	9.053907
2028	73.95753	11.15454	0.924494	1.440323	0.221050	12.30207
2029	67.46829	14.77842	0.810276	1.536251	0.236176	15.17058
2030	61.49886	18.71175	0.721632	1.530830	0.243299	17.29363
2031	56.27870	22.82694	0.655682	1.441919	0.246970	18.54978

Source: author's estimation.

According to the VDA estimates, combustible waste is predicted to impose a larger variance shock of 22.826 percent on carbon emissions, which are expected to climb from 1.287 percent in 2023 to 22.826 percent in 2031. Additionally, the population increase is anticipated to place a substantial burden on environmental quality, with a variance shock of 18.549 percent until 2031, increasing to 0.002 percent in 2023. Industrial, bio waste and MSW recycling would have a 1.441 percent, 0.655 percent, and 0.246 percent variance shock on carbon emissions, respectively, until 2031, illustrating the need to develop sustainable waste management strategies to enhance the country's environmental quality.

4. Discussion

The following significant findings were made as a consequence of the exercise, which aided in the formulation of some solid policy recommendations for the nation, i.e.,

(i) The findings indicate that, on average, educational expenditures require approximately 0.439 percent of gross national income for biowaste recycling, 5.608 percent reduction in chemicals used in manufacturing value-added for industrial waste recycling, and USD2376.166 per capita for municipal solid waste recycling in a country.

(ii) The ARDL estimates demonstrate that industrial waste recycling reduces carbon missions to −0.262 percent in the short term, with the magnitude increasing to −0.721 percent in the long term, confirming that industrial waste recycling contributes to the advancement of an environmental sustainability agenda.Industrial waste recycling is sustainable in a nation if it decreases the number of chemicals utilized in manufacturing value-added. Reduced use of harmful chemicals in manufacturing benefits the environment while also contributing to the country's healthcare sustainability strategy. Earlier studies, which were consistent with the theory of sustainable industrial waste recycling, largely prompted the need for co-efficient industrial waste recycling via innovative geopolymer mortars [52], circular economy elements in products that help minimize food and plastic waste [53], recycling revitalization through a production-oriented approach [54], and cooperative interaction between the parties [55].

(iii) In the next ten years, the VDA expects that biowaste recycling will have a 0.655% greater impact on carbon emissions than it has in the past period. Biowaste recycling required knowledge spillovers to minimize biowaste, while MSW recycling necessitated significant waste funding to manage its waste, resulting in environmental degradation. Sustainable innovations infrastructure is highly acceptable for waste management [56], patenting activities are essential to decrease trash formation [57], and good governance reforms are critical for bio-based circular economy advancement [58]. Sustainable waste management contributes to energy efficiency and economic development by improving environmental quality [59]. The digitalization of technology, anaerobic digestion, and the financial viability of waste-to-energy systems are just a few sustainable methods for managing MSW creation [60–62].

(iv) The causation estimations favored the 'emissions-driven industrial recycling' hypothesis (F-statistics: 4.88364, $p < 0.0128$),which states that carbon dioxide emissions induce industrial recycling in a nation. Irresponsible manufacturing and consumption contribute to increased healthcare issues and are a significant source of air pollution, which has harmed the country's clean and green development strategy [63–66].

(v) Another significant predictor is population growth, which results in increased waste creation and a worsening of environmental quality, as causality estimates confirmed (F-statistics: 5.38116, $p < 0.0086$). Additionally, it placed a greater focus on waste recycling and advocated for the need to develop sustainable waste management methods in a nation. Population expansion exacerbates food production issues and depletes energy supplies, resulting in air pollution [67]. The waste-polluting-pays method may encourage garbage recycling by guaranteeing that waste management strategies have sufficient financing and revenue to thrive [68].

(vi) IRF estimations indicate that biowaste recycling will likely aid in mitigating environmental issues and reducing carbon emissions (IRF estimates: −0.003%) via population ingenuity principles (VDA estimates: 18.549%). Investment in recycling technology, human capital development, cost reduction of recycling, and increased R&D spending would all contribute to a more sustainable waste management process [69–71].

International collaboration, knowledge spillovers, decreased harmful chemicals used in manufacturing, and proper waste finance may assist in rejuvenating economic development via a clean environment.

5. Conclusions and Policy Implications

The United Nations Sustainable Development Goal 12 is about responsible consumption and production, prioritizing waste recycling and waste reduction via sustainable innovation processes. Following the stated objective, this study used time-series data from 1975 to 2020 to analyze various combustible renewables and waste production and recycling and their subsequent influence on carbon emissions in the context of China. The research assessed the influence of biowaste, industrial waste, and municipal solid waste and their recycling procedures on the country's environmental quality using a variety of statistical methodologies that enable the development of country-specific sustainable waste recycling strategies. According to the ARDL estimates, combustible renewables and waste reduce the carbon inventory by boosting industrial waste recycling. However, owing to the considerable output of municipal solid waste, its recycling process is inefficient, necessitating a sustainable method of disposing and recycling the municipal solid waste in a nation. The causality estimations validated the unidirectional correlations between carbon emissions and industrial and municipal trash recycling in a nation, supporting the emission-driven recycling theory. Granger's assertion that population expansion results in carbon emissions, industrial waste recycling, and municipal solid waste recycling bolstered the view that population growth results in emissions and waste recycling. The feedback relationship between waste generation and carbon emissions was discovered, implying that waste generation results in increased emissions per capita in the inventory stock. This relationship reverts when the inventory stock of carbon emissions increases, implying that waste generation results in increased combustible renewables and waste. According to IRF predictions, the waste generating capacity will likely decrease due to increased biowaste recycling and population ingenuity. According to the VDA estimates, carbon emissions stock will likely decrease significantly between 2022 and 2031, from 100% to 56.278 percent, by increasing the percentage of combustible renewables and waste and its recycling activities. This study's results suggest the following policy implications for reorienting the economy towards more responsible consumption and production, i.e.,

(i) As a result of unsustainable economic expansion, managing solid waste has become critical, leading to soil degradation and massive GHG emissions during treatment. The most major element is the continuous transition from a linear to a circular economy, which has increased the public awareness of the hazards associated with technical advancement failing to address environmental deterioration appropriately. Untreated rubbish is the primary source of healthcare mortality and morbidity, necessitating a public–private partnership to manage waste and increase institutional capacity to recycle trash sustainably.
(ii) Significant gains may accrue from waste sorting, collection, transportation, and final disposal improvements. It is vital to link the waste management process to stakeholder involvement and community participation to boost garbage sorting and recycling. If it received more financial backing from public–private partnerships, it might invest more in waste sorting facilities such as collection containers, transport vehicles, and transfer stations.
(iii) Data paucity may result in increased search and transaction costs. It is challenging to locate recyclers and suppliers, and the quality of recyclable or reusable items is unknown. Additionally, it may be asymmetrical, with the supply possessing greater knowledge than the prospective buyer. As a result, there is a higher demand for knowledge regarding garbage recycling and management to educate stakeholders and the general public about waste disposal and its beneficial environmental effects. Garbage pricing should raise the cost of increasing waste generation and create incentives for recycling systems that generate byproducts while maintaining safety.
(iv) Untreated waste dumps, combustion, physically activated carbon adsorption, composting, anaerobic digestion, and recycling are only a few of the worldwide municipal solid waste management's key challenges. The environmental consequences of waste management are related to large methane emissions, which occur due to untreated garbage being landfilled, while burning produces fossil fuel emissions. The advantages of paper recycling and composting over landfilling are contingent on the landfill's ability to reduce landfill gases. As waste reduction technologies and innovation increase, cumulative advantages are anticipated to lessen waste-related climate impacts.
(v) Municipalities seeking to minimize GHG emissions while improving landfill diversion might consider waste-to-energy, mixed waste separation, and collection changes.

The only way to establish whether recycling is environmentally beneficial is to undertake a life-cycle analysis (LCA). The environmental impacts of virgin and recycled materials are compared—utilizing a sound policy mix of regulation, finance, and public awareness in solid waste management.

The "polluter pays" concept should be combined with a trash throw price mechanism to discourage waste and separation. Both pricing schemes should recoup the cost of solid waste management. International cooperation is thought to be desirable in importing cleaner technology and environmentally friendly waste management strategies to maintain a clean environment and achieve eco-sustainability. Strict environmental monitoring and controls should be imposed on polluting businesses, and they should be encouraged to recycle their waste via sustainable production techniques.

Author Contributions: Conceptualization: S., U.A. and K.Z.; methodology: K.Z.; software: K.Z.; validation: S., M.M., U.A., W.H., M.K.J. and M.A.; formal analysis: K.Z.; investigation: S., M.M., U.A., W.H., M.K.J. and M.A.; resources: S., M.M., U.A., W.H., M.K.J. and M.A.; data curation: K.Z.; writing—original draft preparation: U.A. and K.Z.; writing—review and editing: S., M.M., U.A., W.H., M.K.J. and M.A.; visualization: S., M.M., W.H., U.A., M.K.J. and M.A.; project administration: U.A., S., M.M., W.H., M.K.J. and M.A.; funding acquisition: S., M.M., U.A., W.H., M.K.J. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data is freely available at World Development Indicators published by World Bank (2021) at https://databank.worldbank.org/source/world-development-indicators (accessed on 10 June 2022).

Conflicts of Interest: All authors declare no conflict of interest.

References

1. Akmal, T.; Jamil, F. Testing the role of waste management and environmental quality on health indicators using structural equation modeling in Pakistan. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4193. [CrossRef] [PubMed]
2. Anjum, M.S.; Ali, S.M.; Subhani, M.A.; Anwar, M.N.; Nizami, A.S.; Ashraf, U.; Khokhar, M.F. An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review. *J. Hazard. Mater.* **2021**, *402*, 123943. [CrossRef] [PubMed]
3. Sharma, H.B.; Vanapalli, K.R.; Samal, B.; Cheela, V.S.; Dubey, B.K.; Bhattacharya, J. Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery. *Sci. Total Environ.* **2021**, *800*, 149605. [CrossRef] [PubMed]
4. Tabelin, C.B.; Park, I.; Phengsaart, T.; Jeon, S.; Villacorte-Tabelin, M.; Alonzo, D.; Hiroyoshi, N. Copper and critical metals production from porphyry ores and E-wastes: A review of resource availability, processing/recycling challenges, socio-environmental aspects, and sustainability issues. *Resour. Conserv. Recycl.* **2021**, *170*, 105610. [CrossRef]
5. Tong, Y.D.; Huynh, T.D.X.; Khong, T.D. Understanding the role of informal sector for sustainable development of municipal solid waste management system: A case study in Vietnam. *Waste Manag.* **2021**, *124*, 118–127. [CrossRef] [PubMed]
6. Sun, S.; Jin, C.; He, W.; Li, G.; Zhu, H.; Huang, J. Management status of waste lithium-ion batteries in China and a complete closed-circuit recycling process. *Sci. Total Environ.* **2021**, *776*, 145913. [CrossRef] [PubMed]
7. IISD. UN Urges Tackling Waste Management on World Habitat Day. 2018. International Institute of Sustainable Development. Available online: https://sdg.iisd.org/news/un-urges-tackling-waste-management-on-world-habitat-day/ (accessed on 23 April 2022).
8. Cibrario, D. SDG 11: To Ensure Sustainable Waste Services, We Must Value Waste Workers and Make Sure They Are in Decent Jobs. 2018. Available online: https://www.2030spotlight.org/en/book/1730/chapter/sdg-11-ensure-sustainable-waste-services-we-must-value-waste-workers-and-make (accessed on 23 April 2022).
9. Zhang, S.; Chen, W. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nat. Commun.* **2022**, *13*, 87. [CrossRef] [PubMed]
10. Lee, R.P.; Meyer, B.; Huang, Q.; Voss, R. Sustainable waste management for zero waste cities in China: Potential, challenges and opportunities. *Clean Energy* **2020**, *4*, 169–201. [CrossRef]
11. Lombard Odier. How China is Addressing Its Waste Problem. 2021. Available online: https://www.lombardodier.com/contents/corporate-news/responsible-capital/2021/july/how-china-is-addressing-its-wast.html (accessed on 23 April 2022).

12. Huang, H. China's Radical New Rules to Recycle Rubbish. 2019. Available online: https://multimedia.scmp.com/infographics/news/china/article/3038540/china-waste-sorting/index.html (accessed on 23 April 2022).
13. World Bank. *World Development Indicators*; World Bank: Washington, DC, USA, 2021.
14. Bakari, S.; Tiba, S. The Impact of Combustible Renewables and Waste on Economic Growth and Environmental Quality in Tunisia. 2021. Available online: https://mpra.ub.uni-muenchen.de/108616/ (accessed on 23 April 2022).
15. Usman, A.; Ullah, S.; Ozturk, I.; Chishti, M.Z.; Zafar, S.M. Analysis of asymmetries in the nexus among clean energy and environmental quality in Pakistan. *Environ. Sci. Pollut. Res.* **2020**, *27*, 20736–20747. [CrossRef] [PubMed]
16. Maji, I.K.; Adamu, S. The impact of renewable energy consumption on sectoral environmental quality in Nigeria. *Clean. Environ. Syst.* **2021**, *2*, 100009. [CrossRef]
17. Anser, M.K.; Khan, M.A.; Nassani, A.A.; Aldakhil, A.M.; Hinh Voo, X.; Zaman, K. Relationship of environment with technological innovation, carbon pricing, renewable energy, and global food production. *Econ. Innov. New Technol.* **2021**, *30*, 807–842. [CrossRef]
18. Ali, S.; Akter, S.; Fogarassy, C. The Role of the Key Components of Renewable Energy (Combustible Renewables and Waste) in the Context of CO_2 Emissions and Economic Growth of Selected Countries in Europe. *Energies* **2021**, *14*, 2034. [CrossRef]
19. Rădoi, M.I. Environmental Protection: Soil Pollution and Waste Management. *Rev. Ştiinţe Pol.* **2021**, *69*, 167–176.
20. Yu, K.H.; Zhang, Y.; Li, D.; Montenegro-Marin, C.E.; Kumar, P.M. Environmental planning based on reduce, reuse, recycle and recover using artificial intelligence. *Enviro. Impact Assess. Rev.* **2021**, *86*, 106492. [CrossRef]
21. Ahirwar, R.; Tripathi, A.K. E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions. *Environ. Nanotechnol. Monit. Manag.* **2021**, *15*, 100409. [CrossRef]
22. Yousefi, M.; Oskoei, V.; Jonidi Jafari, A.; Farzadkia, M.; Hasham Firooz, M.; Abdollahinejad, B.; Torkashvand, J. Municipal solid waste management during COVID-19 pandemic: Effects and Reper. *Sci. Pollut. Res.* **2021**, *28*, 32200–32209. [CrossRef]
23. Kishor, R.; Purchase, D.; Saratale, G.D.; Saratale, R.G.; Ferreira LF, R.; Bilal, M.; Bharagava, R.N. Ecotoxicological and health concerns of persistent coloring pollutants of textile industry wastewater and treatment approaches for environmental safety. *J. Environ. Chem. Eng.* **2021**, *9*, 105012. [CrossRef]
24. Zamri, M.F.; Hasmady, S.; Akhiar, A.; Ideris, F.; Shamsuddin, A.H.; Mofijur, M.; Fattah, I.R.; Mahlia, T.M. A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110637. [CrossRef]
25. Silva, A.L.P.; Prata, J.C.; Walker, T.R.; Duarte, A.C.; Ouyang, W.; Barcelò, D.; Rocha-Santos, T. Increased plastic pollution due to COVID-19 pandemic: Challenges and recommendations. *Chem. Eng. J.* **2021**, *405*, 126683. [CrossRef]
26. Shah, A.V.; Srivastava, V.K.; Mohanty, S.S.; Varjani, S. Municipal solid waste as a sustainable resource for energy production: State-of-the-art review. *J. Environ. Chem. Eng.* **2021**, *9*, 105717. [CrossRef]
27. Kaur, A.; Bharti, R.; Sharma, R. Municipal solid waste as a source of energy. *Mater. Today Proc.* **2021**. [CrossRef]
28. Gautam, M.; Agrawal, M. Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario. In *Carbon Footprint Case Studies*; Environmental Footprints and Eco-design of Products and Processes; Muthu, S.S., Ed.; Springer: Singapore, 2021. [CrossRef]
29. Qazi, W.A.; Abushammala, M.F. The analysis of electricity production and greenhouse-gas emission reduction from municipal solid waste sector in Oman. *Int. J. Environ. Sci. Technol.* **2021**, *18*, 1395–1406. [CrossRef]
30. Doaemo, W.; Dhiman, S.; Borovskis, A.; Zhang, W.; Bhat, S.; Jaipuria, S.; Betasolo, M. Assessment of municipal solid waste management system in Lae City, Papua New Guinea in the context of sustainable development. *Environ. Dev. Sustain.* **2021**, *23*, 18509–18539. [CrossRef] [PubMed]
31. Zhao, X.; Liu, H.S.; Ding, L.L. Decomposition analysis of the decoupling and driving factors of municipal solid waste: Taking China as an example. *Waste Manag.* **2022**, *137*, 200–209. [CrossRef] [PubMed]
32. Schüch, A.; Morscheck, G.; Lemke, A.; Nelles, M. Bio-waste recycling in Germany–further challenges. *Procedia Environ. Sci.* **2016**, *35*, 308–318. [CrossRef]
33. Zhang, B.; Lai, K.H.; Wang, B.; Wang, Z. Financial benefits from corporate announced practice of industrial waste recycling: Empirical evidence from chemical industry in China. *Resour. Conserv. Recycl.* **2018**, *139*, 40–47. [CrossRef]
34. Zhao, X.; You, F. Waste high-density polyethylene recycling process systems for mitigating plastic pollution through a sustainable design and synthesis paradigm. *AIChE J.* **2021**, *67*, e17127. [CrossRef]
35. Yang, L.; Xiao, X.; Gu, K. Agricultural waste recycling optimization of family farms based on environmental management accounting in rural china. *Sustainability* **2021**, *13*, 5515. [CrossRef]
36. Hsu, S.; Banskota, S.; McCormick, W.; Capacci, J.; Bustamante, C.; Moretti, K.; Martin, K.D. Utilization of a waste audit at a community hospital emergency department to quantify waste production and estimate environmental impact. *J. Clim. Chang. Health* **2021**, *4*, 100041. [CrossRef]
37. Ozcan, B.; Ulucak, R. An empirical investigation of nuclear energy consumption and carbon dioxide (CO_2) emission in India: Bridging IPAT and EKC hypotheses. *Nucl. Eng. Technol.* **2021**, *53*, 2056–2065.
38. Chen, J.; Fan, W.; Li, D.; Liu, X.; Song, M. Driving factors of global carbon footprint pressure: Based on vegetation carbon sequestration. *Appl. Energy* **2020**, *267*, 114914. [CrossRef]
39. Hwang, Y.; Um, J.S.; Schlüter, S. Evaluating the mutual relationship between IPAT/Kaya Identity Index and ODIAC-based GOSAT fossil-fuel CO_2 flux: Potential and constraints in utilizing decomposed VARIABLES. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5976. [CrossRef] [PubMed]

40. Pongrácz, E.; Phillips, P.S.; Keiski, R.L. Evolving the Theory of Waste Management: Defining key concepts. *WIT Trans. Ecol. Environ.* **2004**, *78*, 471–480.
41. Awan, U.; Sroufe, R. Sustainability in the Circular Economy: Insights and Dynamics of Designing Circular Business Models. *Appl. Sci.* **2022**, *12*, 1521. [CrossRef]
42. Awan, U.; Kanwal, N.; Bhutta, M.K.S. A Literature Analysis of Definitions for a Circular Economy. In *Logistics Operations and Management for Recycling and Reuse*; Golinska-Dawson, P., Ed.; EcoProduction; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
43. Alhawari, O.; Awan, U.; Bhutta, M.K.S.; Ülkü, M. Insights from circular economy literature: A review of extant definitions and unravelling paths to future research. *Sustainability* **2021**, *13*, 859. [CrossRef]
44. Awan, U.; Sroufe, R.; Shahbaz, M. Industry 4.0 and the circular economy: A literature review and recommendations for future research. *Bus. Strategy Environ.* **2021**, *30*, 2038–2060. [CrossRef]
45. Cheng, Y.; Awan, U.; Ahmad, S.; Tan, Z. How do technological innovation and fiscal decentralization affect the environment? A story of the fourth industrial revolution and sustainable growth. *Technol. Forecast. Soc. Chang.* **2021**, *162*, 120398. [CrossRef]
46. Khan, R.; Awan, U.; Zaman, K.; Nassani, A.A.; Haffar, M.; Abro, M.M.Q. Assessing Hybrid Solar-Wind Potential for Industrial Decarbonization Strategies: Global Shift to Green Development. *Energies* **2021**, *14*, 7620. [CrossRef]
47. Anser, M.K.; Khan, M.A.; Awan, U.; Batool, R.; Zaman, K.; Imran, M.; Bakar, Z.A. The role of technological innovation in a dynamic model of the environmental supply chain curve: Evidence from a panel of 102 countries. *Processes* **2020**, *8*, 1033. [CrossRef]
48. Awan, U. Steering for Sustainable Development Goals: A Typology of Sustainable Innovation. In *Industry, Innovation and Infrastructure*; Encyclopedia of the UN Sustainable Development Goals; Leal Filho, W., Azul, A.M., Brandli, L., Lange Salvia, A., Wall, T., Eds.; Springer: Cham, Switzerland, 2021. [CrossRef]
49. Awan, U. Industrial Ecology in Support of Sustainable Development Goals. In *Responsible Consumption and Production*; Encyclopedia of the UN Sustainable Development Goals; Leal Filho, W., Azul, A.M., Brandli, L., Özuyar, P.G., Wall, T., Eds.; Springer: Cham, Switzerland, 2020. [CrossRef]
50. Pesaran, M.H.; Shin, Y.; Smith, R.J. Bounds testing approaches to the analysis of level relationships. *J. Appl. Econ.* **2001**, *16*, 289–326. [CrossRef]
51. Narayan, P. *Reformulating Critical Values for the Bounds F-Statistics Approach to Cointegration: An Application to the Tourism Demand Model for Fiji*; Monash University: Melbourne, Australia, 2004; Volume 2.
52. Colangelo, F.; Farina, I.; Travaglioni, M.; Salzano, C.; Cioffi, R.; Petrillo, A. Eco-efficient industrial waste recycling for the manufacturing of fibre reinforced innovative geopolymer mortars: Integrated waste management and green product development through LCA. *J. Clean. Prod.* **2021**, *312*, 127777. [CrossRef]
53. Bigdeloo, M.; Teymourian, T.; Kowsari, E.; Ramakrishna, S.; Ehsani, A. Sustainability and circular economy of food wastes: Waste reduction strategies, higher recycling methods, and improved valorization. *Mater. Circ. Econ.* **2021**, *3*, 3. [CrossRef]
54. Melnykova, M.; Boichenko, M.; Ragulina, N.; Kocheshkova, I. The Task of "recycling-revitalization" as a Priority of Sustainable Development of Ukrainian Industrial Cities. *Eur. J. Sustain. Dev.* **2022**, *11*, 212. [CrossRef]
55. Carfí, D.; Donato, A. Environmental Management through coopetitive urban waste recycling in eco-industrial parks. *Mathematics* **2021**, *9*, 2520. [CrossRef]
56. Babbitt, C.W.; Neff, R.A.; Roe, B.E.; Siddiqui, S.; Chavis, C.; Trabold, T.A. Transforming wasted food will require systemic and sustainable infrastructure innovations. *Curr. Opin. Environ. Sustain.* **2022**, *54*, 101151. [CrossRef]
57. Zwart, R.D. The Contribution of Patenting to A Circular Economy: How Patents on Waste Management Influence Resource Efficiency and Waste Reduction. Ph.D. Thesis, Utrecht University, Heidelberglaan, Utrecht, The Netherlands, 2021. Available online: https://studenttheses.uu.nl/handle/20.500.12932/917 (accessed on 23 April 2022).
58. Cong, R.G.; Thomsen, M. Review of ecosystem services in a bio-based circular economy and governance mechanisms. *Ecosyst. Serv.* **2021**, *50*, 101298. [CrossRef]
59. Razzaq, A.; Sharif, A.; Najmi, A.; Tseng, M.L.; Lim, M.K. Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions and energy efficiency using a novel bootstrapping autoregressive distributed lag. *Resour. Conserv. Recycl.* **2021**, *166*, 105372. [CrossRef]
60. Kurniawan, T.A.; Lo, W.; Singh, D.; Othman, M.H.D.; Avtar, R.; Hwang, G.H.; Shirazian, S. A societal transition of MSW management in Xiamen (China) toward a circular economy through integrated waste recycling and technological digitization. *Environ. Pollut.* **2021**, *277*, 116741. [CrossRef] [PubMed]
61. Seruga, P. The municipal solid waste management system with anaerobic digestion. *Energies* **2021**, *14*, 2067. [CrossRef]
62. Abushammala, M.F.; Qazi, W.A. Financial feasibility of waste-to-energy technologies for municipal solid waste management in Muscat, Sultanate of Oman. *Clean Technol. Environ. Policy* **2021**, *23*, 2011–2023. [CrossRef]
63. Sadiqa, B.A.; Zaman, K.; Rehman, F.U.; Nassani, A.A.; Haffar, M.; Abro, M.M.Q. Evaluating race-to-the-top/bottom hypothesis in high-income countries: Controlling emissions cap trading, inbound FDI, renewable energy demand, and trade openness. *Environ. Sci. Pollut. Res.* **2022**, *29*, 50552–50565. [CrossRef] [PubMed]
64. Kumar, R.; Verma, A.; Shome, A.; Sinha, R.; Sinha, S.; Jha, P.K.; Vara Prasad, P.V. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* **2021**, *13*, 9963. [CrossRef]

65. Lee, T.C.; Anser, M.K.; Nassani, A.A.; Haffar, M.; Zaman, K.; Abro, M.M.Q. Managing Natural Resources through Sustainable Environmental Actions: A Cross-Sectional Study of 138 Countries. *Sustainability* **2021**, *13*, 12475. [CrossRef]
66. Jiang, Q.; Khattak, S.I.; Ahmad, M.; Lin, P. Mitigation pathways to sustainable production and consumption: Examining the impact of commercial policy on carbon dioxide emissions in Australia. *Sustain. Prod. Consum.* **2021**, *25*, 390–403. [CrossRef]
67. Rehman, A.; Ma, H.; Ozturk, I.; Ulucak, R. Sustainable development and pollution: The effects of CO_2 emission on population growth, food production, economic development, and energy consumption in Pakistan. *Environ. Sci. Pollut. Res.* **2022**, *29*, 17319–17330. [CrossRef] [PubMed]
68. Okudo, A.; Omojolaibi, J.A.; Mubarak, O. Impact of Waste Recycling On Environmental Quality and Revenue Generation: Case Study of University Of Lagos, Nigeria. *Int. J. Contemp. Res. Rev.* **2021**, *12*, 20211–20277.
69. Yu, Z.; Khan, S.A.R.; Ponce, P.; Muhammad Zia-ul-haq, H.; Ponce, K. Exploring essential factors to improve waste-to-resource recovery: A roadmap towards sustainability. *J. Clean. Prod.* **2022**, *350*, 131305. [CrossRef]
70. Mele, M.; Magazzino, C.; Schneider, N.; Gurrieri, A.R.; Golpira, H. Innovation, income, and waste disposal operations in Korea: Evidence from a spectral granger causality analysis and artificial neural networks experiments. *Econ. Politica* **2022**, *39*, 427–459. [CrossRef]
71. Cui, Y.; Chang, I.S.; Yang, S.; Yu, X.; Cao, Y.; Wu, J. A novel dynamic business model to quantify the effects of policy intervention on solid waste resourcelization industry: A case study on phosphogypsum resourcelization in Yichang, China. *J. Clean. Prod.* **2022**, *355*, 131779. [CrossRef]