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Improving Natural Resource Efficiency: The Role of Eco-Innovation, Recycling, Waste Management, Youth Education and Digital Finance to Promote Sustainability

Xiaotian Xu[1], Fang Yang[2]*

[1]Business School, Hubei University
Wuhan, Hubei Province, 430062, China
E-mail. 201701111200023@stu.hubu.edu.cn

[2]School of Special Education, Zhengzhou Normal University*
No. 16 Yingcai Street, Huiji District, Zhengzhou, Henan Province, 450044, P.R. China
*E-mail. xuxiaotian1126@163.com (*Corresponding Author)*

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This research has addressed the crucial significance of natural resource efficiency for achieving sustainable development, specifically between contemporary environmental challenges. However, previous research has highlighted the relevance of eco-innovation, recycling of waste management, youth education, and digital finance for sustainability, their combined impact on natural resource efficiency remains undiscovered. The study focused on China and Korea over the period of 2000 to 2022, employing advanced panel data econometric techniques, which include Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), for empirically testing these variables on natural resource efficiency. The outcomes shows that eco-innovation, recycling, youth education, and digital finance have significantly contributed towards enhancing the efficient use of natural resources. The outcome underscores the synergistic role of technological innovation, educational advancement, sustainable waste practices, and digital financial platforms for promoting sustainable developments. The policy implications focus on the significance of integrating these factors for fostering responsible resource sustainability in resource-abundant economies.

Keywords: *Natural Resource Efficiency; Eco-Innovation; Recycling; Waste Management; Digital Finance; Sustainability.*

Introduction

The Natural resources have provided a strong basis for social and economic development. There is a rapid increase in industrialization and population, that demands for natural resources that has been surged over the period of years as large scale use of natural resources required for these processes. Global eco-system has faced severe challenges which results from less efficient use of natural resources. However, the sustainable use of natural resources has become significant for creating a balanced world ecosystem (Tan *et al.,* 2023). Therefore, in the era of sustainable development, the natural resources' effective management appears as an important concern, highlighting the crucial requirement for strategies that are innovative to digital finance, waste management, eco-innovation, recycling and education of youth. Eco-innovation is the major aspect in this context, providing a way to redesign our interactions with the environment, introducing products that are novel, mechanism and technologies with a purpose to reduce the influence on environment. As Gomes et al. (2024) discusses that, eco-innovation includes the innovative and sustainable substitutes in production of food involving the use of insects as a food source which is sustainable, thereby outlining the significance to potentially provide contribution towards the sustainability of environment. Eco-innovation is helpful for adjusting and improving

The allocation and utilization of natural resource efficiency and raw material. They could adjust and improve the use and allocation of natural resources, generating different energy efficient products and raw materials which could enhance the utilization of efficient energy and raw materials for improving the output efficiency of natural resources. Although, the relationship between eco-innovation and natural resource efficiency has been theoretically explained in literature, and less attention has been paid for empirically researching on innovation of natural resource efficiency (Miao *et al.*, 2017).

Similarly, waste management and recycling plays an important role in natural resource efficiency with an emphasis on recycling, reduction and reuse of materials to reduce the stress on environment. Recycling is a more environmentally friendly waste management technique as compared to incineration or landfilling and enables the safety of the scarce resources and allows landfill space to be saved (Andre & Cerda, 2006; Liu *et al.*, 2025).

As natural resources are the major source of production materials, the recycling degree of any resource (and its nature of being renewable or non-renewable) must be taken into consideration to select inputs in production process. When one is concerned with sustainability and the long-term development of the economy, these issues are especially important (Andre & Cerda, 2006). By keeping resources for as long as possible providing a promising route for attaining resilience and sustainability for resource management with a decrease of waste generation and increasing the recycling of resource flows (Arsakhanova *et al.,* 2024, Bachnik & Nowacki, 2024).

Furthermore, the significance of education to achieve sustainability cannot be avoided. Youth education to promote practices of sustainability confirms the development of environmentally conscious generation, which is excited to implement and focus on sustainable lifestyle. The importance of education relates with the broader objective of attaining sustainable development, as awareness and knowledge are basic to enhance a sustainability culture among the future generations. With help of moral persuasion and eco-friendly education, it is important to get knowledge that how many people are conscious for the environment, those who follow the ethical norms and moral in their regular routine and influenced by reduction in carbon. At several stages, education provides several opportunities to get knowledge about energy efficiency and natural resource management. The lack of education and literacy is a main factor contributing to the natural resources depletion. More emphasis on improvement of environmental and social literacy and knowledge leads towards more awareness regarding the issue related to foster energy efficiency and use of renewable resources leading to efficient use of natural resources (Shao *et al.,* 2023).

In the same vein, digital finance is one of the most important components of the digital economy. Digital finance arises as one other critical variable, providing solutions for innovative finance which provides support to projects of environment and to the initiative that are developed for sustainable development. By implementing the digital platforms, the resources can be mobilized by stakeholders, thereby enhancing the transformation towards an economy which is sustainable. The digital finance' role to encourage sustainability and eco-innovation projects outlines the synergistic significance of finance and technology to advance the objectives of environment.

Moreover, there is a growing focus towards sustainability, eco-innovation, and natural resource management, there are several critical gaps that remined unaddressed in current body of literature, specifically concerning the determinants of natural resource efficiency for rapidly industrializing regions such as Korea and China. First and the most prior studies determine individual sustainability drivers such as eco-innovation, digital finance, recycling, waste management and education in isolation without acknowledgement of interdependencies and potential synergies effects. For instance, eco-innovation has been widely studied as a catalyst for the reduction of environmental degradation (Chen, Yi, & Zhang, 2022; Zemlickienė *et al.*, 2025; Nicoletti & Appolloni, 2024; Che, 2025), and recycling practices have been associated with sustainable waste utilization Liu *et al.,* 2021), very few studies have integrated technological, financial, educational, and environmental dimensions within a unified framework. This approach limits the understanding of how these variables collectively shape the natural resource efficiency, a multidimensional construct that needs a holistic analytical perspective. The present research has therefore not sufficiently captured the relationship between innovation ecosystem, financial accessibility, public awareness and institutional waste management systems (Zhang & Wang, 2021; Khatami *et al.,* 2024).

Second, however sustainability research has been expanded significantly, so much of literature tends to emphasize on macro-level environmental indicators such as carbon emissions, greenhouse gases, and indices of pollution rather than directly determining natural resource efficiency as a distinct outcome. Studies involving education systems often explore their influence on CO_2 emissions or environmental quality (Xie *et al.,* 2023; Elom *et al.,* 2024; Hsu, 2024), but empirical evidence on how youth education particularly through environmental awareness, values, and knowledge contributes to efficient natural resource consumption remains sparse. The lack of specificity regarding educational impacts creates a theoretical gap because youth education is widely recognized as a driving force behind pro-environmental behavior, responsible consumption, and sustainable resource use (Kahriman-Ozturk *et al.,* 2012; Lee *et al.,* 2025). Yet quantitative evidence linking youth education systems directly to measurable improvements in natural resource efficiency is significantly underdeveloped.

Third, the methodological rigor in prior studies presents major limitations. Many investigations utilize cross-sectional data, case studies, or country-specific analyses (Li & Lin, 2016), which restrict the generalizability and reliability of findings over time. Consequently, empirical rigor suffers, preventing the development of robust policy recommendations. Additionally, despite the growing role of digital finance in facilitating environmental investments, supporting green projects, and enabling data-driven sustainability practices (Zhou *et al.,* 2023), its interaction with eco-innovation, recycling systems, and youth education has not been thoroughly examined. The co-evolutionary effects of these variables remain missing in empirical sustainability research.

Fourth, a significant geographical gap persists in the literature. While extensive studies have examined sustainability issues in Western or highly developed nations (OECD regions), research focusing on China and Korea is comparatively limited, despite these countries' rapid industrialization, urbanization, and increasing natural resource consumption. Their distinct socio-economic structures, environmental challenges, and policy frameworks differ markedly from those of Western economies. Most existing cross-country studies aggregate data from heterogeneous countries, obscuring context-specific dynamics and overlooking the unique institutional, technological, and cultural characteristics of East Asian economies (Park & Lee, 2020; Lulaj & Mekaniwati, 2025; Xiao & Qu, 2025). As such, there is insufficient empirical evidence tailored to the regional realities of China and Korea, both of which face pressing concerns regarding resource depletion, waste accumulation, and the need for sustainable development pathways.

Finally, the psychological and behavioural dimensions of youth education, including environmental knowledge, perceived behavioural control, sustainability orientation, and pro-environmental values identified as significant predictors of sustainable behaviour (Aminrad, Zakariya, & Hadi, 2013; Zhao *et al.,* 2024) have not been meaningfully integrated into quantitative models of natural resource efficiency. The absence of these nuances limits the explanatory power of existing studies, which often treat education as a simple demographic or enrolment indicator rather than a transformative mechanism that shapes long-term sustainable behaviours.

Therefore, the current study seeks to address these gaps by (i) examining the combined and interactive effects of eco-innovation, digital finance, youth education, and recycling/waste management on natural resource efficiency; (ii) applying robust panel econometric methods (FMOLS and DOLS) using longitudinal data from 2000–2022; and (iii) situating the analysis within the specific socio-economic contexts of China and Korea to provide nuanced insights for policymakers and sustainability practitioners. By filling these gaps, the study offers a comprehensive, integrative contribution to the literature on sustainable development and resource efficiency, aligned with the guiding principles of SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

Keeping the above background into consideration, the present study aims at investigating the role of eco-innovations, digital finance, youth education, recycling and waste management in natural resource efficiency in China and Korea over 2000 to 2022 period. Natural resource efficiency is one of the major determinants of sustainable development in resource abundant countries like China and Korea. Rapid urbanization and industrialization in these countries have exaggerated the stress on natural resources as shown in Figure 1 which raise concerns about long-run sustainability. Although the living standard in China has improved significantly and has contributed substantially in global growth, but the country has faced environmental challenges despite being abundant in natural resources. The yearly consumption of natural resources in country has been rising continuously over the years, which requires more efficient and productive use of natural resources. Efficient utilization of the natural resources is necessary to attain a healthy and sustainable consumption of natural resources (Yanbing Liu, Lu, Xian, & Ouyang, 2023; Khan *et al.*, 2024). Likewise, Korea has undergone rapid deforestation over the years which resulted in the reduction of its natural resources and forest cover. Moreover, the country has been suffering from the resource curse hypothesis despite being full of resources which can be attributed to the inefficient consumption and mismanagement of natural resources (Shittu *et al.*, 2021). The following research questions are going to be answered by the present study in particular:

1. What is the effect of eco-innovations on natural resource efficiency?
2. What is the effect of digital finance on natural resource efficiency?
3. What is the effect of youth education on natural resource efficiency?
4. What is the effect of recycling and management of waste materials on natural resource efficiency?

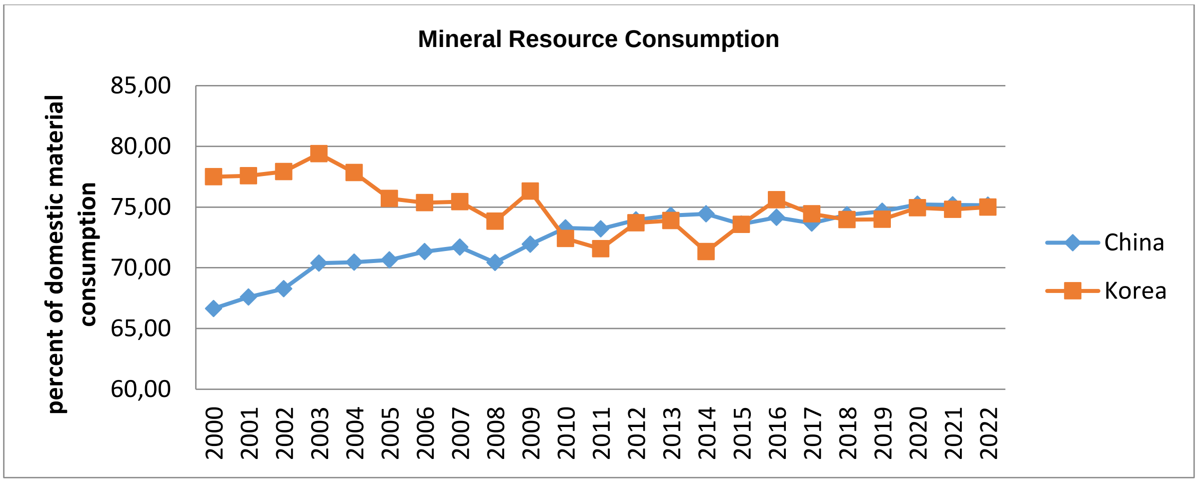

Figure 1. Rate of Resource Consumption in China and Korea (2000 to 2022)
Source OECD (2024)

The study holds its significance to the existing body of the literature in the following ways: First, despite of the broad literature on waste management, eco-innovation, recycling, digital finance and youth education in enhancing sustainability (Al-Braizat, 2016; Aydin *et al.*, 2023; Kulekci & Guvendi, 2023; Ozturk & Ullah, 2022; Tariq & Shahzad, 2022), there exists a potential gap to get knowledge regarding the influences of these variables on enhancement of natural resource efficiency in China and Korea. The study has an objective to bridge this gap by evaluating the synergistic influence of these key determinants on improving the efficiency of natural resources and enhance sustainable development in China and Korea. The potential of this research is based on its significance to offer a strong knowledge how the related variables can be effectively used to attain goals of sustainable development such as SDG 13 (climate change mitigation) and SDG 12 (responsible consumption and production), thereby contributing towards the more integrated environment for policy formulation and initiatives that are important in the global context for sustainable development.

There are various sections in this research paper, after introduction there will review of literature regarding existing studies on the study variables, methodology outlines the use of advanced panel data technique in this paper by using Korea and China data, results section will present the findings and discuss will interpret the implications along with limitations and future suggestions.

Literature Review

Eco-Innovation and Sustainability

Eco-innovation refers to the process of using latest technology and business models for the development of new products and the latest business models aimed at reducing the environmental impact of resources by increasing resource efficiency and fostering the sustainability (Garcia-Granero *et al.,* 2018). It uses the innovation processes that are meant to create solutions for the positive environment and contributes to the economic growth as well as the social well-being of people. Additionally eco-innovation has been identified as key driver for changing transition towards sustainability as it would allows the development of competitive technologies which hold great environment benefits (Kemp, 2010, Dabbous *et al.,* 2024). There are various aspects that are linked with eco-innovation technology like the use of green technologies and environmentally friendly material which is used for sustainable processes and the production methods which help in addressing environmental challenges. The integration of these technologies helps in the promotion of sustainable future and create environment that contributes to the well-being of people. The development of new ideas and technologies help in minimizing the resource consumption and reducing the overall impact on environment hence promoting the sustainability across industries.

According to Cainelli, D'Amato, and Mazzanti (2020), the use of green technologies and eco-friendly material help in the efficient use of natural resources by reducing the energy consumption and promoting circular economy practices which help in the extending the life of product so that there is no need of more raw material for manufacturing of new product. Similarly, the sustainable production processes help in the utilization of natural resources efficiently. There are certain resource optimization strategies like lean manufacturing and resource recovery that enhances the overall productivity of resources. The use of eco-innovation helps in minimizing the ecological carbon emission and conserve resources for future use and the efficient use of resources helps in the reduction of waste and lower the production cost of goods (Yunqiang Liu *et al.,* 2020).

In the existing literature, the ample evidence is present regarding the influence of eco-innovations on environmental sustainability, with little attention given to their role in natural resource efficiency, For instance, taking panel data of G-7 economies, Akram, Ibrahim, Wang, Adebayo, and Irfan (2023) studied the impact of eco-innovations, green energy and natural resource dependence in achieving carbon neutrality over the period 1997 to 2019. Ibrahim, Awosusi, Ajide, and Ozdeser (2023) analyzed the role of technological innovations, nuclear energy, non-renewable energy, urbanization and services value added in carbon emission in BRICS countries over 1992 to 2019 period. The outcomes of the MMQR estimation indicated that technological innovations, non-renewable energy and urbanization promotes, while nuclear energy and services value added reduced carbon emissions.

In case of emerging seven (E-7) countries, Niu, Niu, Ibrahim, and Al-Faryan (2023) studied the relationship between financial development, natural resource dependence, and environmental sustainability over 1995 to 2019 period. The study verified that negative and positive shocks from natural resources promoted environmental pollution whereas the positive shocks of financial development moderated carbon emissions whereas negative shocks enhanced carbon emissions. In the context of G-7 countries, Ibrahim, Al-Mulali, et al. (2023) analysed the role of demographic mobility, technological advancement and energy transition in environmental sustainability over 2000 to 2019 period. Likewise, Shen, Ridwan, Raimi, and Al-Faryan (2023) studied the role of green hydrogen, environmental related technologies, green finance, energy efficiency and digitalization in top green hydrogen consuming countries over 1995 to 2019 period. The results of the study obtained by applying AMG, CCEMG and MMQR approach indicated that these factors promoted environmental sustainability whereas urbanization and natural resources increased CO_2 emissions. Taking China as case study, Q. Zhang, Adebayo, Ibrahim, and Al-Faryan (2023) studied the impact of shocks in technological innovations in environmental sustainability over 1990 to 2019 period through NARDL modelling. The outcomes established that positive shocks in technological innovations promoted, but negative shocks reduced environmental sustainability in China.

In the same vein, Qi, Ibrahim, and Saleh Al-Faryan (2023) studied the role of eco-innovations, biofuels, affluence, population, coal and green finance in carbon emissions in top biofuel abundant economies over 1995 to 2019 period using AMG, CCEMG and CS-ARDL approaches and found that coal, population and affluence promoted CO2 emissions whereas green finance, eco innovations and biofuels reduced CO_2 emissions. In the context of BRICS economies, A. Wang, Shan, Ibrahim, and Omokanmi (2024) analysed the role of green finance, green energy, eco-digitalization, urbanization and green innovations in environmental sustainability over 1995 to 2019 period and the findings endorsed that green innovations, green finance, green energy and eco-digitalization promoted, but affluence and urbanization reduced environmental sustainability.

Y. Wang, Ibrahim, Oke, and Al-Faryan (2024) studied the role of green energy, government expenditures, technological innovations, structural change and financial development in environmental sustainability in Africa over 1990 to 2018 period. The outcomes from CS-ARDL, MMQR, AMG and CCEMG revealed that technological innovations, structural changes and green energy promoted, whereas financial development and government expenditures reduced environmental sustainability.

Considering panel data of 5 highest carbon emitting African countries, Shen, Ibrahim, Ajide, and Al-Faryan (2024) studied the role of technological innovations, renewable energy, natural resource dependency, structural transition and urbanization on environmental pollution from 1990 to 2019 period. The outcomes of AMG, CCEMG and CS-ARDL estimation techniques indicated that structural transition, renewable energy and technological innovations reduced environmental pollution. In case of China, Han, Ibrahim, Al-Mulali, and Al-Faryan (2024) studied the symmetric impact of green innovations, renewable energy, green finance and eco-digitalization on environmental sustainability in China using ARDL model. All of these factors were found to promote environmental sustainability in China according to the outcomes of the FMOLS, DOLS and Canonical Cointegration regression.

Likewise in BRICS economies, Zhou, Bin Samsurijan, Ibrahim, and Al-Faryan (2024) explored that how natural resources (total as well as disaggregated) impact environmental sustainability over 1995 to 2019 period. The outcomes established that natural resources impeded environmental sustainability in BRICS countries. Likewise, taking panel of 54 African countries, Zhou, Samsurijan, Ibrahim, and Ajide (2024) studied the role of renewable and non-renewable energy, trade openness, and institutions in sustainable development over 1996 to 2019 period. The outcomes verified that non-renewable energy and trade openness hindered sustainable development whereas renewable energy promoted it. The interaction term of institutional quality enhanced sustainable development.

In the presence of technological innovations, renewable energy and foreign direct investment, Zou, Yang, Ibrahim, and Al-Faryan (2024) studied the ecological effects of demographic mobility and structural transformation in five top emitter countries in Africa over 1990 to 2019 period. According to the outcomes of CS-ARDL, CCEMG, AMG and MMQR approaches, structural transformation and demographic mobility increased CO2 emissions which were significantly moderated by technological innovations, renewable energy and foreign direct investment. In case of G-7 economies, (Dong, Ibrahim, Ozturk, & Al-Faryan, 2024) analysed the impact of natural resources, technological innovations, carbon tax and green energy on environmental sustainability over 1996 to 2019 period. Using CS-ARDL, CCEMG and MMQR approaches, the study found that except natural resources, all other variables promoted environmental sustainability in the selected countries.

Recycling and Waste Management

Recycling is the process in which the waste material is converted into useful products in order to avoid the waste of useful material. It also helps in the reduction of energy and usage of raw material. This process involves collecting, sorting, processing of materials like glass, paper and converting them into new products (Jorgensen, 2019). The use of recycling and waste management practices help in the promotion of sustainable development, and it holds benefits for both environment as well as society. The recycling process also requires less energy for the production of goods as compared to other processes and reduces the emission of gases that can pollute the environment. The use of proper waste management systems helps in fixing the waste properly and restricts the harmful substance from entering into the environment.

According to Zorpas (2020), the social benefits of the use of recycling and waste management include reduction in the exposure to hazardous substance that could impact the health of the people and their well-being. It also raises awareness among people regarding responsible consumption and empowers individuals to take part in sustainable practices. This practice also addresses the social inequalities and promotes the access of resources and clean environment for all by promoting social inclusion. The primary objective of this process is to reduce the negative impact of waste on environment and health and maximize the resource recovery which helps in the promotion of sustainable practices (Nanda & Berruti, 2021).

Empirically, André and Cerdá (2006) studied the dynamic impact of recycling on natural resources and found that in the short run, recycling eliminated the resource scarcity, but had no effect in the long run. Bayar, Gavriletea, Sauer, and Paun (2021) studied the role of municipal waste recycling in CO_2 emissions over 2004 to 2017 period in EU countries through panel causality and cointegration analysis. Razzaq, Sharif, Najmi, Tseng, and Lim (2021) studied the impact of municipal waste recycling on environmental quality and economic growth in the USA over 1990 to 2017 period. Findings of Bootstrapping ARDL model indicated that municipal waste recycling enhanced economic growth and reduced CO_2 emissions in the USA. Guoyan, Khaskheli, Raza, and Ahmed (2022) analysed the non-linear impact of recycling of solid municipal waste on environmental sustainability and economic growth over 1990 to 2018 period.

Ibrahim (2022) analysed the role of resource dependence, trade openness and energy consumption in carbon neutrality in G-20 economies over 2001 to 2019 period. FMOLS, GMM and Quantile regression estimations revealed that non-renewable energy, coal rents, oil rents and imports increased, but renewable energy, exports and gas rents reduced the carbon emissions. Omokanmi, Ibrahim, Ajide, and Al-Faryan (2022) analysed the impact of natural resources and environmental pollution on longevity in resource dependent African countries over 1980 to 2019 period. The findings of FMOLS, DOLS and quantile regression endorsed that both environmental pollution and natural resources reduced longevity.

Similarly, using quarterly data for the USA over 1990 to 2018 period, Razzaq, Sharif, Afshan, and Li (2023) analysed the impact of recycling on consumption based CO_2 emissions and the outcomes of QARDL approach endorsed that recycling mitigated consumption based CO_2 emissions. Considering the panel of top 10 resource dependent countries, Ibrahim, Huang, Mohammed, and Adebayo (2023) analysed the role of natural resources in CO_2 emissions covering the time period 1995-2019. The results of CS-ARDL, AMG and CCEMG approaches revealed that natural resources exacerbated CO_2 emissions which were moderated by renewable energy, technology, green finance and structural change. Taking into consideration the panel of leading countries in nuclear energy, Pan, Adebayo, Ibrahim, and Al-Faryan (2023) studied the role of nuclear energy in environmental sustainability over 1990 to 2019 period. The quantile-on-quantile regression revealed that nuclear energy promoted environmental sustainability in some of the selected countries whereas it reduced environmental sustainability in other countries.

Digital Finance

Most countries are focusing on financial growth and development for boosting economic growth that could be achieved this by efficiently allocating the resources (Shahbaz *et al.,* 2022). However, the financial development emphasizes economic growth, the importance and magnitude of effect that varies depending specific context (Boikos *et al.,* 2022, Yuqing Cai *et al.,* 2025). Digital finance refers to the use of digital technologies in order to deliver financial services that are helpful for individuals as well as businesses. This process use diverse financial activities which are connected digitally through certain channels. There is also a facility of digital wallet in which the information related to payment is saved and used when it is needed by the customer. This helps in purchasing goods and services and receiving money digitally (Ozili, 2018). This platform also helps businesses and individuals to raise funds from various sources in large amount for a cause by running online campaigns for any start up or charitable cause. Digitalization is playing a significant role for speeding up accessibility, and safety, it also speeds up the decline in intensity of energy, according to (Liang, 2024). According to Pazarbasioglu et al. (2020), FINTECH involves online banking that facilitate customers to perform their banking transactions remotely. Similarly another service includes mobile payments in which the users make transactions using their devices like smartphones and this service promotes contactless payments.

According to Bollaert, Lopez-de-Silanes, and Schwienbacher (2021), the digital finance provide variety of financial products like green bonds, carbon credits, and environmental friendly payment options. The solutions also incorporate risk management tools that help in reduction of climate risks, and natural disasters. The integration of sustainability criteria in risk assessment helps in supporting resilience for business. There are certain benefits associated with sustainable resource management by the use of digital finance. The tools of digital finance i.e. online banking, digital wallet, and online payments help in the reduction of paperwork and surpass the traditional method. This allows business to allocate resources effectively (Feng, Zhang, & Li, 2022). This platform also provides access to real time data and analytics that provide information regarding financial insights and help stakeholders in making informed decisions. Digital finance also promotes financial inclusion by providing access to digital banking and investment opportunities to populations that are residing in remote areas and this inclusion also helps in their participation in sustainable resource management practices and help to tackle environmental risks.

Literacy and Development

Youth education is necessary for the promotion of sustainability as the sustainable future can be fostered by empowering youth and developing knowledge and skills in them required to address environmental challenges. The education of youth needs to integrate the concepts of sustainability in social, economic, and environmental prosperity. Education fosters critical thinking skills among students so that they can think out of the box and provide solution to certain problems by evaluating different perspectives. Students are provided with hand on experience so that youth get the knowledge of practical world and they can apply their knowledge in practice. Education also emphasizes on the ethical considerations and values that contribute towards the betterment of the environment and society which help in maintaining the beliefs and norms of society. The students also learn about diverse cultures and global challenges and develop a sense of shared responsibility. The youth education cultivates a long-term impact and encourages the students to practice the sustainable consumption patterns and behaviours.

In the existing literature, in the context of China, Ma (2022) analysed the role of educational human capital in total factor energy efficiency over 2008 to 2020 period and concluded that educational human capital had negative impact on total factor energy efficiency in China and its regions. Shao et al. (2023) studied the role of education in resource efficiency in five BRICS countries over 1995 to 2021 period. The findings of the study using PMG-ARDL technique revealed that education had no positive impact on resource efficiency. Xie, Saeed, Akhter, and Kumar (2023) examined the impact of higher education on CO_2 emissions over 1995 to 2019 period in top Asian countries using CS-ARDL analysis. The results showed that higher education increased CO_2 emissions. RUK (2024) analyzed the role of education expenditures in CO_2 emissions over 1998 to 2020 period in BRICS countries. Using fisher cointegration analysis, it was found that education expenditures improve resource usage which helps reduce CO_2 emissions. Elom et al. (2024) studied the role of investment in education in CO_2 emissions using the panel data of African countries over 2000 to 2018 period and the outcomes of FMOLS, FEOLS, Driscoll-Kraay standard error approach and panel cointegration approaches revealed that investment in education has negative impact on CO2 emissions.

Method

Theoretical Framework and Model Specification

The first theory that best explain our study and provides basis for the model specification is the Innovation diffusion theory which explains that how the use of new technologies and ideas are adopted within a society and it also identifies key strategies for influence of adoption process (Al-Rahmi *et al.,* 2019). This theory explains the advantage of using certain policies and helps in the promotion of sustainability. This theory basically shows the stages and mind set for innovation adoption for any policy, product or service. Innovation adoption is required to attain sustainable development in any sector (Khan *et al.,* 2022). This theory is applicable to our study as it helps in providing insights related to the factors that influence adoption of sustainable innovations and also identifies barriers and opportunities for the promotion of eco-friendly initiatives. Hence, the basic form of the model becomes:

$$NRE_{it} = \alpha_0 + \beta_1 EI_{it} + \varepsilon_{it} \quad (1)$$

Next, the ecological modernization theory hypothesizes that environmental issues arisen due to economic activities can be neutralized by the efficient utilization of the resources through circular economy practices such as recycling and waste management and technological innovations that improve a country's economic and environmental performance. Resource conservation and waste mitigation are highlighted to be strongly associated with economic performance and environmental sustainability (Razzaq *et al.,* 2021). Similarly, digital economy practices are an example of technological progress, which create opportunities for economic recovery and sustainable development. It is believed that digitalization brings ecological modernization in production, which ensures the resource savings and the sustainable development of countries and the territories (Li, Liu, & Ni, 2021). Therefore, following the underpinnings of the ecological modernization theory and studies of (C. Zhang, Yang, Yan, & Wang, 2023) and André and Cerdá (2006), the present study estimates the impact of recycling and waste management and digital finance on natural resource efficiency, and the equation (1) becomes:

$$NRE_{it} = \alpha_0 + \beta_1 EI_{it} + \beta_2 WM_{it} + \varepsilon_{it} \quad (2)$$

Moreover, according to Salamatov, Gnatyshina, and Gordeeva (2019), education, which is an important source of information supports ecological modernization, therefore, following the study of Shao et al. (2023), we incorporate youth education as an important determinant of natural resource efficiency and the equation (2) takes the following form:

$$NRE_{it} = \alpha_0 + \beta_1 EI_{it} + \beta_2 WM_{it} + \beta_3 DF_{it} + \beta_4 LR_{it} + \varepsilon_{it} \quad (3)$$

Moreover, following Tan et al. (2023) and Tiwari (2024), economic growth is added as control variable to the baseline model and the resultant model takes the following form:

$$NRE_{it} = \alpha_0 + \beta_1 EI_{it} + \beta_2 WM_{it} + \beta_3 DF_{it} + \beta_4 LR_{it} + \beta_5 EG_{it} + \varepsilon_{it} \quad (4)$$

Where,

NRE= Natural resource efficiency
EI= Eco-innovation
WM= Waste minimization
LR= Literacy rate
DF= Digital finance
EG= Economic growth

Variables Specification

The dependent variable in the present study is natural resource efficiency. To operationalize the variable, we opted for data on natural resource rents which is available on World Development Indicators (WDI). The indicator takes into account all natural resources, including coal, oil, gas, forest and minerals, and is used as a proportion of the gross domestic product. For measuring recycling and waste, data is extracted from Organization of Economic Cooperation and Development. Digital finance is measured using the proxy of digital accounts from WDI while youth education is gauged using literacy levels. The literacy level is assessed from the indicator of enrolment in primary and secondary schools assessed from WDI. Lastly, eco-innovation is estimated using the environmental patents by OECD. Data lies in the range from 2000 to 2022. The measurement details of the selected variables are given in Table 1.

Table 1

Measurement of the Variables and Data Sources

Variables	Measurement	Data Source
Natural resource efficiency	Total natural resource rents (% of GDP)	WDI
Recycling and waste management		OECD
Digital finance	Digital accounts	WDI
Youth education	Literacy rate	WDI
Eco-innovations	Patents in environmental related technologies (% of all technologies)	WDI
Economic growth	GDP growth (annual %)	WDI

Econometric Methods

The variables in the panel dataset underwent unit root analysis. The unit root analysis comprised of applying different tests to confirm the stationarity characteristics. The tests assume non-stationarity as the null hypothesis i.e., presence of a unit root; thus, when the null hypothesis is not supported, it is concluded that the data does not possess a unit root i.e., stationarity data. This is followed by the evaluation of the co-integration associations in the panel data set variables. This evaluation was carried out by using Fully Modified Ordinary Least Squares (FMOLS).

FMOLS Estimator

The FMOLS estimator is selected for the determination of the long-run coefficients of the variables understudy. Initially developed by Phillips and Hansen (1990), the FMOLS technique was further enhanced by Pedroni (2001) to account for panel cointegration regression, providing researchers the benefit of addressing issues related to endogeneity and autocorrelation. The FMOLS estimation approach was adopted by Rahman, Khattak, Ahmad, and Khan (2020) to uncover the dynamic association between energy consumption and economic growth while Sarfraz, Naseem, and Mohsin (2022) also used the FMOLS technique to evaluate the linkages between natural resources, information technology and economic growth. These studies indicate the growing applicability of FMOLS in panel datasets. It is advocated that the FMOLS technique is appropriate and suitable in panel datasets as it provides certain advantages. For instance, as it controls for serial correlation and endogeneity and therefore regarded superior as compared to other estimators (Sarfraz *et al.*, 2022). In addition, the superiority of FMOLS lies in its provision of reliable and consistent estimation. Even in datasets with small sample size, FMOLS offers unbiased results (Amna Intisar *et al.*, 2020). The FMOLS estimator is demonstrated in the equation below:

$$\widehat{\beta^*}\text{FMOLS} = N^{-1} \sum_{i=1}^{N} \widehat{\beta^*} \text{ FMOLS} \quad (5)$$

Empirical Results

Descriptive Statistics

The descriptive summary of the variables under consideration is exhibited in the table 2. A total of 44 observations are reported for each variable, verifying the absence of any missing value. The table also reports the mean, median and range of the variables. For the assessment of normality, metrics such as skewness, kurtosis and Jarque-Bera (JB) are utilized. Skewness values indicate that recycling, literacy rate and digital finance are negatively skewed while other variables exhibited positive skewness. In addition, kurtosis values that exceed the threshold of 3 imply high peak with a thin bell-shaped curve. Normality in all data series is not confirmed as the JB statistic has the probability values greater than 0.05 which demonstrate that total natural resources, recycling, patents and literacy rate do not stick to normal distribution. On the other hand, with low JB values, both GDPG and digital finance adhere to normal distribution.

Table 2

Summary Statistics

	TNR	RECY	PAT	LITs	GDPG	DGF
Mean	1.771216	17901.92	71464.34	8.795455	6.296764	83.82785
Median	0.492614	18316.60	46895.50	9.000000	6.777299	92.35680
Maximum	9.648414	22644.60	159019.0	9.000000	14.23086	140.5659
Minimum	0.031135	0.000000	26560.00	6.000000	-0.709415	6.744725
Std. Dev.	2.422418	4152.901	42407.62	0.701478	3.340138	36.78560
Skewness	1.507708	-3.657208	0.803328	-3.383046	0.161008	-0.514698
Kurtosis	4.534831	16.54131	2.154883	13.07077	2.432996	2.254700
Jarque-Bera	20.98881	434.2575	6.041868	269.8676	0.779510	2.961066
Probability	0.000028	0.000000	0.048756	0.000000	0.677223	0.227516
Sum	77.93352	787684.4	3144431.	387.0000	277.0576	3688.425
Sum Sq Dev.	252.3288	7.42E+08	7.73E+10	21.15909	479.7303	58186.75
Observations	44	44	44	44	44	44

Cross-Sectional Dependence

As panel data is a combination of both time and cross-sectional elements, there is likelihood that dependence exists among the units in the cross-sections. Generally, in analysis involving economic and development indicators, cross-sectional dependence can occur due to global shocks or underlying factors which makes the obtained results biased and inefficient. The cross-sectional dependence is assessed using several tests in the present study as depicted in Table 3. The results validate the absence of cross-sectional dependence as the statistically insignificant p-values indicate that the null hypothesis cannot be rejected and therefore study confirms that cross sectional units are independent.

Table 3

Cross-Sectional Dependence Analysis

Test	Statistic	Prob.
Breusch-Pagan Chi-square	0.330950	0.5651
Pearson LM	-1.887304	0.0591
Pearson CD	-0.575282	0.5651
Friedman Chi-square	14.94545	0.8257

Cointegration

Following the confirmation of cross-sectional independence, the next step is to evaluate the presence of long-term association using Kao Cointegration Test. The result shown in Table 4 indicates that the null hypothesis of "no cointegration" is rejected which validate that co-integration relationship exists among the variables.

Table 4

Cointegration Analysis

	t-Statistic	Prob.
ADF	-1.628683	0.0517
Residual variance	1.378163	
HAC variance	0.728433	

FMOLS Outcomes

This study relied on the FMOLS technique to investigate the associations between the dependent and independent variables. Table 5 demonstrates the findings from the analysis which specify that lagged value of total natural resources (TNR) is significantly and positively associated with the current value. Thus, a significant association between past value of TNR and current value has been reported in the findings. Similarly, there is a significant and negative impact of recycling on TNR. Additionally, current value environmental patents (PAT) are negatively associated with TNR whereas lagged value of PAT is positively associated. Both the impacts are statistically significant at a 1 % significance level. These results imply that while current patents impact TNR negatively, the delayed effect of patent on TNR is positive. Increase in environmental patents leads to an increase in TNR.

The association between LIT and TNR is also positive and significant, indicating that education of youth has a significant and positive impact on TNR. Moreover, the study also examined the association between GDP growth and TNR and the findings indicated a positive and significant relationship between them. Increase in GDP leads to a rise in TNR. Lastly, the findings demonstrate that lagged value of DF negatively and significantly influences TNR, implying that the delayed effect of DF on TNR is negative. On the other hand, the current value of DF is positively related to TNR. The impact of current DF is also significant at a 1% significance level. These outcomes are graphically shown in Figure 1.

Table 5

FMOLS Estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TNR(-1)	3841.929	13.49059	284.7859	0.0000
RECY(-1)	-0.006797	0.000391	-17.39737	0.0000
PAT	-0.003613	0.000172	-21.03818	0.0000
PAT(-1)	0.009365	0.000160	58.40844	0.0000
LIT	32.65051	0.972250	33.58241	0.0000
GDPG	12.27346	0.323635	37.92376	0.0000
DF(-1)	-16.26977	0.233264	-69.74826	0.0000
DF	12.80347	0.239598	53.43728	0.0000

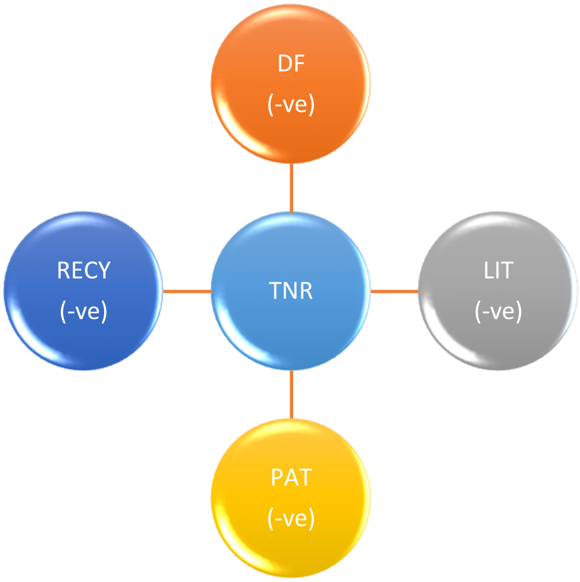

Figure 1. Graphical Representation of the FMOLS Outcomes

DOLS Outcome

Along with FMOLS, the Dynamic OLS (DOLS) is employed to further check the robustness of the estimates obtained previously. The DOLS technique has been frequently utilized in combination with FMOLS in panel data analysis (Gyamfi, Onifade, Nwani, & Bekun, 2022; Tugcu, 2018). The findings of the DOLS analysis are depicted in Table 6. Similar to the FMOLS estimate, lagged TNR has a positive impact on current TNR. Recycling also has a statistically significant impact on TNR. However, the impact of recycling on TNR is positive as per the DOLS analysis. Parallel to FMOLS estimation, PAT significantly affects TNR in China and Korea. Current levels of eco-innovation positively influence TNR. In the DOLS estimation, LIT is negatively associated with TNR and the association is supported statistically at a 10 % significance level. Contrary to FMOLS estimation, GDPG does not have a significant influence on TNR. Similarly, DF was also found to be an insignificant predictor of TNR. As per the R-squared value, 82 % of the variation observed in TNR is explained by the independent variables in the model which indicates good predictive power

Table 5

DOLS Estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TNR(-1)	0.377887	0.141755	2.665784	0.0126
RECY(-1)	0.000694	0.000273	2.540144	0.0169
PAT	0.000166	4.19E-05	3.956017	0.0005
PAT(-1)	-8.83E-05	4.28E-05	-2.063874	0.0484
LIT	-0.939323	0.542974	-1.729958	0.0946

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDPG	-0.153858	0.115336	-1.333998	0.1930
DF(-1)	-0.129599	0.078526	-1.650405	0.1100
DF	-0.033180	0.068153	-0.486848	0.6302
R-squared	0.879760			
Adjusted R-squared	0.823934			

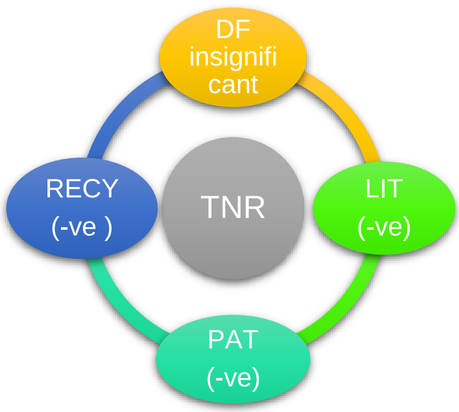

Figure 2. Graphical Representation of the DOLS Outcomes

Normality Check

Lastly, the normality of the residuals is tested, as depicted in the figure 3 below. With a small JB value and a p-value of 0.33 (> 0.05), the assumption of normality was not violated.

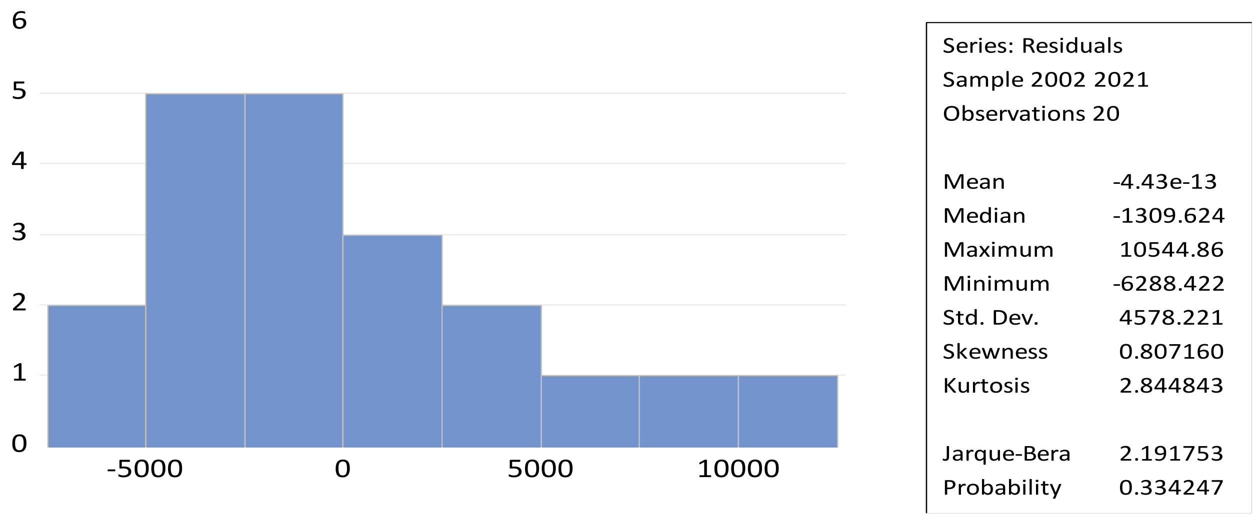

Figure 3. Graphical Representation of Residual Normality

Discussion

Discussion, Conclusion and Policy Implications

This study has used the FMOLS and DOLS techniques to evaluate the associations between the variables. Recycling has a significant role in promoting sustainability as it is found to enhance the efficient use of the natural resources. This implies that recycling and the utilization of waste material reduces the burden of pollution from the environment and adheres to the concepts of sustainability. The process of recycling reduces the need of extracting material for the production of new products and helps in the preservation of natural resources like forests and water (Pujara *et al.*, 2019). The outcomes of the study are supported by (Wiśniewska, Saeb, & Bencherif, 2023) who found recycling as a promising factor for reducing the negative environmental effects of depletion and enhancement of sustainability. Likewise, the findings of the present research are also supported by André and Cerda (2006) who conclude that recycling eliminates resource scarcity.

Next, youth education is also found to promote sustainability by efficient utilization of the natural resources. This implies that higher education has tremendous impact on the youth's habits and their attention to the non-profit societal and environmental prospects. This finding is justifiable as the educated people are more likely to have an understanding of the importance of the environmental factors and their preservation, and therefore they show sustainability-oriented behaviors. Moreover, they show prominent concern for the accurate implementation of the natural resources conservation strategies. The outcomes of Nousheen, Zai, Waseem, and Khan (2020) supports the findings of the present study by concluding that sustainability oriented education of the students plays a significant role in a sustainable future. Another research targeted the same association but investigated a global perspective. Likewise, the findings of Žalėnienė and Pereira (2021) also support the present research by highlighting that higher education acts as a major facilitator in polishing the young generation's minds for sustainability globally. Thus, the study verified that youth education is significant in driving their sustainability goals and practices.

Similarly, eco-innovations are also evident to enhance sustainability by promoting the efficient use of natural resources. This is an expected outcome as environmental friendly technologies enables the efficient resource use which result in lower demands for material on both supply and demand sides (Leitao, Ferreira, & Santibanez-Gonzalez, 2022). From the existing literature, Miao et al. (2017) support the findings of the study by arguing that eco-innovations enhanced the efficiency of natural resource utilization in China. The results of Zheng (2024) also corrobate the findings by concluding the contribution of eco-innovations in promoting total factor energy productivity.

In the last, the analysis revealed mixed results for the digital finance. The FMOLS results supported the significant impact of digital finance for sustainability and the DOLS results rejected it. A possibility of this difference can be that DOLS performs better in short run dynamics (Mark & Sul, 2003) and it is possible that digital finance has insignificant impact on resource efficiency in the short run. This can be because of the delay in the implementation of the tools of digital finance in underserved or rural areas which can impact resource efficiency. However, the study has overall perceived digital finance as a supportive factor for resource efficiency. The tools of digital finance help in the efficient allocation of the resources by reduction of paperwork and surpassing the traditional method in business operations (Feng *et al.*, 2022). These outcomes are supported by Macchiavello and Siri (2022) who highlighted that digital finance in the form of Fintech has major settings to sustain the environment. The outcomes are also in line with Hu and Li (2024) who argued that digital economy promotes natural resource efficiency in China.

In conclusion, this study was a radical practice addressing several important constructs in sustainable development. This study was based on investigating the role of eco-innovation, recycling, waste management, youth education and digital finance in promoting sustainability. The FMOLS technique supported all designed associations and highlighted that digital finance, youth education, and recycling, total environmental safety in the form of waste management all have significant promising role in increasing and promoting sustainability. Meanwhile, the DOLS technique showed significant outcomes for all variables except digital finance and GDP.

With these condensed notes and the whole research strategy, the study has put forward some significant recommendations for the practitioners and policy makers. The study has shared the empirical knowledge that recycling and waste management are very fruitful practices because they have multi-dimensional supportive systems with sustainability and environmental regulations. So, these practices can be promoted by the practitioners, and policymakers to effectively manage environmental pollution and increase environmental sustainability. For this purpose, financial support should be given to the businesses to facilitate them adopt the recycling practices and households and businesses must be charged for producing non-recycle able wastes. Furthermore, technologies and projects aimed at producing recycle able and biodegradable materials must be encouraged by the governments.

Moreover, the study also highlighted the importance of the demographical factor i.e., education in increasing sustainability. With this insight, the study has implied that education, green knowledge, awareness of sustainability, and acknowledgment about the importance of the environment and natural resources have a direct link with people's orientation towards sustainable and environmentally friendly behaviors, attitudes and activities. So, the government can raise different campaigns and awareness programs to promote sustainability awareness among youth in countries. Government should formulate and implement policies to promote free secondary education to overcome financial constraints and invest in infrastructure development such as buildings and digital inclusion to facilitate education activities in remote areas. Moreover, governments must provide financial assistance for research and development activities to promote eco-innovations as these are found to promote efficient use of natural resources.

The study has also highlighted the prevalence of digital finance in increasing the sustainability standard. So, the professional workers in the field or industries and the government should pay attention to raise the importance of digital financing and emphasize the business world and other contemporary world stakeholders to show maximum utilization of digital finance in the form of different sustainable financing activities. With all these contributions, this study has portrayed many useful and important factors for the practitioners, policymakers and the federation of every country that is surrounded by the issue of sustainability.

Limitations and Future Research Directions

There are certain limitations in the present study. First, this study used a quantitative secondary approach to address the main objective and no other research strategy was utilized.

As evident from the basic overview of the addressed constructs, they can be efficiently investigated with the other research strategies like quantitative primary data research by targeting a specific population like university students or fresh graduates. Next, this study has accessed the impact of limited variables on the sustainability. In literature, many individual or personal instinct-based factors also exist that have a more certain role in orienting the youth towards sustainability such as individual awareness level, perceived values and environmental knowledge (Chwialkowska *et al.*, 2020; Diallo *et al.*, 2021; Polas *et al.*, 2023). So, future studies can extend the spectrum of this study by adding more literature-supported variables in sharpening sustainability orientation.

In addition to the recommended variables, the next studies can also target the deteriorating factors of the sustainability like intensive industrialization, heavy economic growth, pollution, harmful gas emissions like CO_2, Ozone, and different nitrates and sulfates in addition to natural resource management. Moreover, this study has been conducted in a defined geographical boundary and it confines its implied contributions to the specific region. Future studies can elongate the prevalence of the addressed idea by targeting other demographical and geographical areas and elaborating new interesting facts for the literature. Thus, all these narrated limitations and highlighted future suggestions may facilitate the future researchers in initiating their research journey.

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Authors' Biographies

Xiaotian Xu is a student at the Business School of Hubei University, China. His research interests focus on business management, finance, and emerging trends in organizational development. Xiaotian has actively participated in academic projects and studies aimed at understanding contemporary business strategies and market dynamics. He can be reached via email at 201701111200023@stu.hubu.edu.cn. ORCID: 0009-0006-7735-5397

Fang Yang is a researcher and faculty member at the School of Special Education, Zhengzhou Normal University, China. As the author, Fang Yang specializes in special education, inclusive teaching strategies, and educational research aimed at improving learning outcomes for students with diverse needs. They have contributed to various academic studies and projects in the field of special education. ORCID: 0009-0004-3365-792X

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