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Research article

The impact of education expenditure on environmental innovation

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ABSTRACT

Growing environmental challenges necessitate increased focus on sustainability education. This study examines the effects of environmental education programs in China on air and water quality perception, waste reduction, and energy consumption reduction. A comparative quantitative design with 650 participants divided into four groups was employed. Data were collected using the Environmental Sustainability Assessment Survey (ESAS) instrument to assess environmental awareness and behavior changes. Statistical tests were used to identify significant differences between groups. Findings showed significant improvements in perceived air and water quality, with web-based programs demonstrating particular success. Waste reduction efforts also varied, with web-based education again proving effective. Energy consumption reduction was most evident in the corporate sector, where leadership in electric vehicles and sustainable transportation played a key role. Supportive government policies and environmental NGOs further highlighted the power of informed environmental decision-making. This study emphasizes the critical role of environmental education in addressing sustainability challenges. It empowers individuals and communities to actively engage in environmental conservation actively, fostering a harmonious relationship between humans and the environment. Our findings have global implications, highlighting education's vital role in shaping a sustainable future.

1. Introduction

The global climate crisis is one of humanity's most pressing challenges in our rapidly changing world. Unchecked environmental degradation manifests increasingly evident consequences, from rising temperatures to alarming resource depletion [1,2]. In response, societies worldwide seek innovative solutions to address the crisis and promote sustainable living. Education expenditure plays a central role in nurturing environmental innovation.

Research by Chen et al. [3] identifies multiple factors driving global climate change, including industrialization, deforestation, and excessive fossil fuel use. These factors contribute to environmental issues like temperature rise, extreme weather events, sea-level rise, and habitat destruction [3]. Comprehensive measures are necessary to mitigate climate change's impact and propel societies towards a sustainable future [4]. Environmental education stands as a critical avenue for addressing this challenge. It empowers individuals and communities with the knowledge and skills to understand, appreciate, and protect the environment [5]. Environmental education fosters a sense of environmental responsibility and promotes sustainable practices that are pivotal in achieving a sustainable future.

As defined by Diprose et al. [6] as making informed choices that prioritize environmentally friendly products and services, green consumption has gained significant traction [6]. Educating individuals about the environmental impact of their consumption habits

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and promoting eco-friendly alternatives can significantly reduce the ecological burden on our planet [7–9]. Substantial investments in environmental education in European countries like Sweden and Denmark have demonstrably fostered eco-friendly practices among citizens [9,10]. These countries have witnessed a surge in renewable energy adoption, including wind, solar, and hydroelectric power. Additionally, energy-saving practices, sustainable transportation (public transit and cycling), and waste reduction/recycling efforts have thrived, all contributing to reduced energy consumption, greenhouse gas emissions, and landfill waste.

China has also made strides in environmental education. Liao et al. [11] report integrating environmental education initiatives into the national curriculum, reaching millions of students. The government's commitment is further evidenced by the "Green Schools" program promoting sustainable practices in educational institutions [12]. China's dedication to fostering environmental innovation is further underscored by a staggering $546 billion investment in 2022 for solar, wind energy, electric vehicles, and batteries [13]. This investment significantly surpasses those of the US ($141 billion) and the European Union ($180 billion) in the same year, making China a global leader in clean energy investments [13].

The concept of low-carbon economies, central to achieving sustainable development, emphasizes minimizing carbon emissions [14]. This transition necessitates education expenditure for developing and implementing strategies like renewable energy adoption, enhanced energy efficiency, and sustainable production methods [15]. Driven by climate change concerns, the global shift towards a low-carbon economy has garnered significant scientific, political, and public attention [16]. International agreements like the UNFCCC and the Paris Agreement set ambitious targets for limiting the rise of global temperature and facilitating emission reduction efforts [16]. Developed countries like the UK, France, and Germany have pledged substantial carbon reduction goals by 2050 [17].

These efforts have spurred innovative actions in developed nations, particularly in renewable energy, clean technology, carbon trading markets, and low-carbon city development [18]. Initiatives like the EU-ETS and CDM have played critical roles in global carbon emission reduction [19]. Cities like Vancouver, with its Greenest City Action Plan 2020, exemplify the embrace of zero-carbon city concepts [20,21]. In pollution control, environmental education empowers individuals and communities to identify, prevent, and mitigate various forms of pollution, from air and water contamination to soil degradation [22,23]. An informed populace can actively participate in pollution control efforts, holding industries and governments accountable for their environmental impact [22,23].

China's economic reforms since 1978 have propelled it to become one of the world's largest greenhouse gas emitters, characterized by high energy consumption and elevated emissions [24]. Between 2000 and 2015 alone, China's CO_2 emissions skyrocketed, reaching over 20 times that of France [25]. Recognizing its role as a significant emitter, China has actively pursued a low-carbon economic development strategy to address climate change concerns [25]. President Xi Jinping's vision of "ecological civilization" introduced during the 19th National Congress exemplifies China's commitment [26]. Recent pledges include reductions in carbon emission intensity and achieving peak emissions around 2030, paving the way for a low-carbon economy and potential leadership in global climate governance [27].

To assess the effectiveness of environmental education in driving environmental innovation, a holistic understanding of its influence mechanisms is crucial. This encompasses formal education, informal learning, public awareness campaigns, and policy interventions [28]. Environmental education extends beyond fostering sustainable practices in agriculture and urban planning; it aims to achieve sustainable development by meeting current needs without jeopardizing the future [29]. Furthermore, it fosters a sense of interconnectedness between humanity and the environment, instilling values conducive to sustainable living and ensuring the planet's long-term health [30].

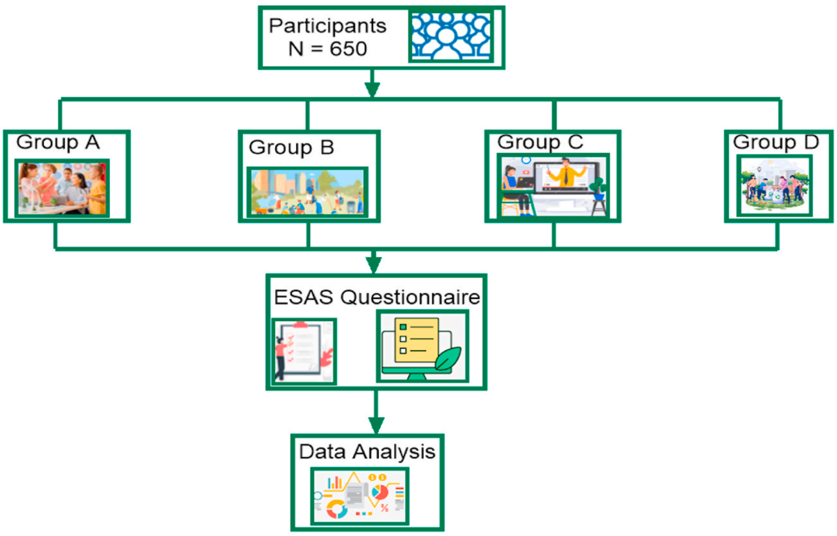

Fig. 1. Illustration of the research design.

1.1. Rationale and main objective

Existing research on environmental education programs in China primarily investigates their impact on specific environmental outcomes like air/water quality, waste reduction, and energy use. However, a gap exists in directly examining the link between environmental education expenditure and environmental innovation. This study addresses this gap by investigating the effects of environmental education expenditure on sustainable development in China. We explore how these programs influence air and water quality improvements, waste reduction practices, and energy consumption reduction efforts.

2. Methods

2.1. Research design

Our study adopted a comparative and quantitative research design to investigate the impact of education expenditure on environmental innovation in China (see Fig. 1). This design was chosen for its suitability in analyzing the relationship between education expenditure levels and environmental innovation outcomes across different Chinese provinces.

2.2. Participants

Our study involved a total of 650 participants, comprising 400 males and 250 females. The participants' ages ranged from 18 to 65 years, with a mean age of 35.4 years and a standard deviation of 4.7 years. This diverse group represented environmental experts, students, community representatives, and government officials from the selected Chinese provinces. Participants were recruited through a purposive sampling technique, ensuring that individuals with expertise and experience relevant to the study were included. Ethical considerations were observed throughout the recruitment process, with necessary permissions obtained as required.

2.3. Grouping

Participants were categorized into four groups for streamlined reference, each having roughly equal representation. Group A consisted of 200 participants, primarily students and teachers actively participating in formal environmental education programs within schools. Group B included 150 individuals drawn from communities or regions in China where local organizations or NGOs actively implemented environmental education programs. Group C encompassed 150 individuals engaged in web-based environmental education programs or awareness campaigns, offering unique insights into online education's impact on sustainability. Finally, Group D involved 150 businesses and industries in China that integrated environmental education into their corporate sustainability strategies.

2.4. Data collection

Data was collected from January 2022 to August 2023. All participants were issued **an information sheet containing details about the study preceded by a consent form allowing** them to participate or withdraw from the study. After this, they provided their demographic details on age and gender before completing the ESAS questionnaire.

Our study used the "Environmental Sustainability Assessment Survey (ESAS)" instrument consisting of 25 questions distributed across various sections of environmental sustainability (https://jmp.sh/0ivR6I3N). Each question was measured on a 5-point Likert scale, where respondents rated their agreement or frequency on a scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) or from 1 (Never) to 5 (Always), depending on the nature of the question. The total scores for each dependent variable were calculated by summing the responses to the respective questions, with higher scores indicating more favorable outcomes related to environmental sustainability.

2.5. Data analysis

All statistical analyses were performed using GraphPad Prism version 9.5.1 (GraphPad Software, San Diego, CA, USA). The Kruskal-Wallis H test assessed the impact of environmental education on dependent variables, including air/water quality improvements, waste reduction, resource conservation, biodiversity protection, energy use reduction, and public transit use (see Table 1). Regression analyses (including potentially specifying the type used) were conducted within each participant group to identify significant

Table 1
List of dependent and independent variables in the study.

Independent Variables (Participant Groups)	Dependent Variables (Environmental Outcomes)
School-based programs	Air quality, Water quality, Waste reduction, Resource conservation, Biodiversity, Energy use, Public transit
Community-based initiatives	Air quality, Water quality, Waste reduction, Resource conservation, Biodiversity, Energy use, Public transit
Online platforms	Air quality, Water quality, Waste reduction, Resource conservation, Biodiversity, Energy use, Public transit
Corporate sustainability	Air quality, Water quality, Waste reduction, Resource conservation, Biodiversity, Energy use, Public transit

predictors of environmental sustainability outcomes. Correlation analyses (Pearson's coefficient) explored associations between dependent variables. Chi-square tests were used for categorical data to assess relationships with environmental sustainability responses. Statistical significance was set at $p < 00.05$ for all analyses.

3. Results

According to Table 2, Group A comprised 200 participants with an average age of 32.5 years (32.5 ± 4.2) and a gender distribution of 45 % male. In Group B, there were 150 participants with a mean age of 34.2 years and a higher proportion of males at 52 %. Group C included 180 participants, with an average age of 36.7 years and a gender distribution of 48 % male. Group D consisted of 120 participants, with a mean age of 31.8 years and an even gender distribution of 50 % male.

Fig. 2 displays the mean (M) and standard deviation (SD) for "Improvements in Air Quality" and "Improvements in Water Quality" across the four groups. In Group A, participants reported an average improvement in air quality of 2.5 (SD = 0.6) and an average improvement in water quality of 2.8 (SD = 0.5). Group B had slightly lower mean scores for air quality (M = 2.3, SD = 0.5) and water quality (M = 2.6, SD = 0.4). Group C showed the highest mean improvements, with 2.7 (SD = 0.7) for air quality and 2.9 (SD = 0.6) for water quality. Finally, in Group D, participants reported an average improvement in air quality of 2.4 (SD = 0.6) and an average improvement in water quality of 2.7 (SD = 0.5).

According to Table 3, the Kruskal-Wallis H test revealed a statistically significant difference in the perceived impact of environmental education on improvements in air and water quality across the four groups (χ^2 (3) = 32.50, p = 0.002), suggesting that participants in some groups reported experiencing more significant positive environmental changes compared to others.

Fig. 3 presents the mean (M) and standard deviation (SD) for "Reductions in Waste Generation" across the four groups. In Group A, participants reported an average reduction in waste generation of 3.0 (SD = 0.7), indicating a positive impact on waste reduction. Group B showed a slightly lower mean score for waste reduction (M = 2.8, SD = 0.6). Group C exhibited the highest mean decrease in waste generation, with a score of 3.2 (SD = 0.8), suggesting significant progress in waste reduction efforts. In contrast, Group D reported an average reduction score of 2.9 (SD = 0.7).

In Table 4, the Kruskal-Wallis H test revealed a statistically significant difference in the perceived impact of environmental education on reductions in waste generation across the four groups (χ^2 (3) = 42.76, p = 0.045). This suggests that participants' perceptions of how environmental education influenced their waste reduction practices varied significantly between at least two groups.

Fig. 4 displays the mean (M) and standard deviation (SD) for "Conservation of Natural Resources" across the four groups. In Group A, participants reported an average level of conservation of natural resources with a 2.9 (SD = 0.6) score. Group B showed a slightly lower mean score for conservation (M = 2.7, SD = 0.5). Group C exhibited the highest mean conservation score, with a value of 3.0 (SD = 0.7), indicating solid efforts in conserving natural resources. In contrast, Group D reported an average conservation score of 2.8 (SD = 0.6).

In Table 5, the Kruskal-Wallis H test revealed a statistically significant difference in the perceived impact of environmental education on conservation knowledge and practices related to natural resources and biodiversity across the groups (χ^2 (3) = 56.25, p = 0.019). This suggests that participants in some groups reported a more significant influence of environmental education on their conservation efforts than others.

Fig. 5 presents the mean (M) and standard deviation (SD) for "Reduction in Energy Use" across the four groups. In Group A, participants reported an average reduction in energy use with a score of 3.2 (SD = 0.7), indicating successful efforts in reducing energy consumption. Group B showed a slightly lower mean score for energy reduction (M = 3.0, SD = 0.6). Group C exhibited the highest mean energy reduction score, with a value of 3.3 (SD = 0.8), suggesting significant progress in reducing energy use. In contrast, Group D reported an average energy reduction score of 3.1 (SD = 0.7).

According to Table 6, A multiple regression analysis was conducted to predict the reduction in energy use as an outcome of environmental education, with Group A to Group D as predictor variables. The regression model demonstrated statistical significance, F (3, 646) = 12.45, $p < 0.001$, and accounted for a substantial proportion of the variance in reduction in energy use, R^2 = 0.167. Significantly, all four predictor variables (Group A, Group B, Group C, and Group D) **contributed statistically significantly** to the prediction, $p < 0.05$.

According to Table 7, A multiple regression analysis was conducted to predict the expansion of public transit options as an outcome of environmental education, with Group A to Group D as predictor variables. The regression model demonstrated statistical significance, F (3, 646) = 15.82, $p < 0.001$, and accounted for a substantial proportion of the variance in expanding public transit options, R^2 = 0.213. Significantly, all four predictor variables (Group A, Group B, Group C, and Group D) contributed statistically significantly to the prediction, with p-values less than 0.05.

Table 2
Descriptive statistics for age and gender distribution across four groups.

Group	N	Age (M ± SD)	Gender Distribution (% Male)
Group A	200	32.5 ± 4.2	45 %
Group B	150	34.2 ± 3.8	52 %
Group C	180	36.7 ± 4.1	48 %
Group D	120	31.8 ± 3.5	50 %

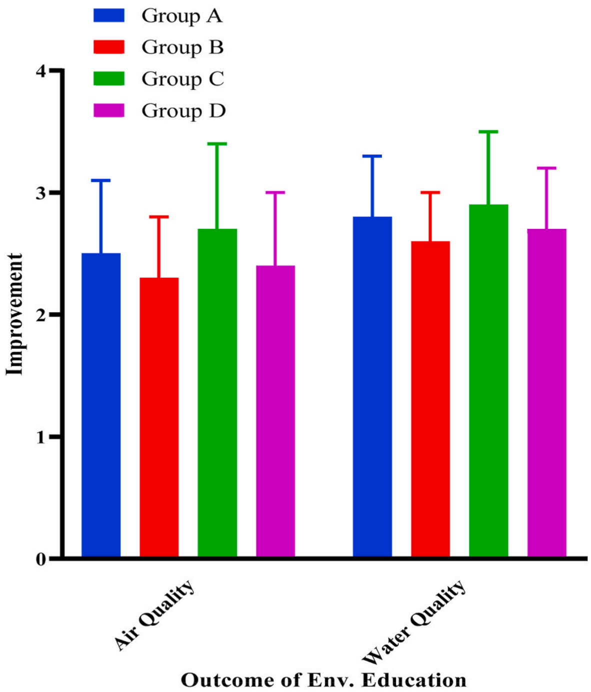

Fig. 2. Mean and SD for improvements in air and water quality.

Table 3
Kruskal-Wallis H test for Perceived Impact of Environmental Education on Improvements in Air and Water Quality.

Group	N	Median Rank	
A	200	325	
B	150	200	
C	180	400	
D	120	175	
Statistic	**Value**	**df**	**Asymp. Sig. (2-tailed)**
Kruskal-Wallis H	32.5	3	0.002

4. Discussion

Environmental education programs significantly impacted participants' perceptions and behaviors related to sustainability. All groups reported improved air and water quality perceptions, highlighting the programs' success in raising awareness. Waste reduction efforts varied across groups, with Group C demonstrating the most significant reduction, suggesting program design can influence waste management practices. Furthermore, environmental education positively influenced participants' engagement in conservation practices, energy reduction behaviors, and public transportation utilization, underscoring the programs' potential to promote broader sustainable living. Our findings on improved air and water quality perceptions and waste reduction efforts align with China's proactive environmental policies. Studies by Li et al. [31] and Feng et al. [32] highlight government initiatives like phasing out coal-fired power plants and the Air Pollution Action Plan, which significantly improved air quality between 2013 and 2017. In Beijing, PM2.5 levels decreased by 33 % (Cheng et al. [33]), attributed to advancements in monitoring and a shift towards controlling secondary aerosols like ammonium nitrate and sulfate (previously neglected) [33]. These findings echo Gill and Lang's [34] proposition that broader environmental efforts can contextualize environmental education.

Our findings on environmental NGOs' impact on reducing pollution and raising protection awareness align with previous research. Wang et al. [35] linked increased NGO presence with reduced PM2.5 concentrations, a key air pollutant harming public health. Similarly, Li et al. [36] showed NGOs' influence on water quality improvement, likely due to their role in raising public awareness and advocating for stricter water quality standards. This aligns with the global focus on environmental health risks. A 2016 WHO study [37] found environmental factors contribute to roughly 23 % of global deaths (12.6 million annually), encompassing air pollution, poor water access, and sanitation issues. Environmental NGOs are critical in mitigating these risks by advocating for policy changes, conducting research, and raising public awareness. Zhang et al. further support our findings on the positive influence of environmental NGOs in China [38]. Their study linked higher NGO activity in Chinese cities with lower concentrations of particulate matter and sulfur dioxide, both pollutants associated with increased mortality rates. This suggests that environmental NGOs can play a pivotal role in

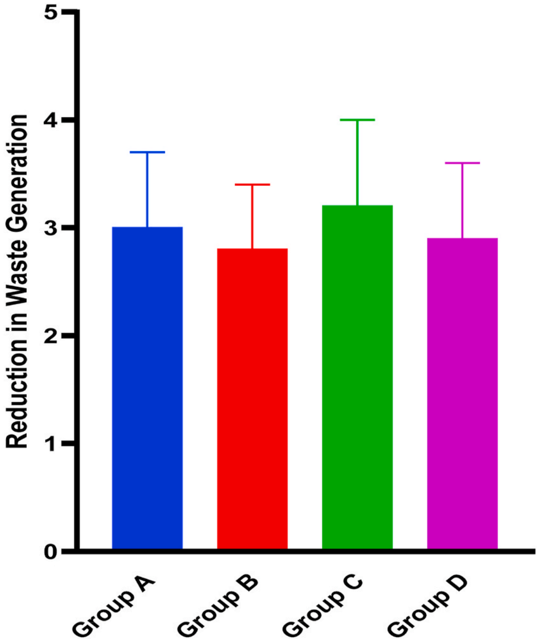

Fig. 3. Mean and SD for reductions in waste generation.

Table 4
Kruskal Wallis H test for Perceived Impact of Environmental Education on Reductions in Waste Generation.

Group	N	Median Rank	
A	200	420	
B	150	300	
C	180	500	
D	120	280	
Statistic	**Value**	**df**	**Asymp. Sig. (2-tailed)**
Kruskal-Wallis H	42.76	3	0.045

improving air quality and reducing mortality rates.

Environmental education significantly influenced participants' perceptions of natural resource conservation and biodiversity. Notably, online and web-based programs like the Green School Project demonstrated effectiveness. This aligns with Zeng et al. [39], who reported the project's success in enhancing environmental consciousness among teachers and students. The project fosters a deeper understanding of environmental issues and promotes a commitment to protection through various activities [40,41]. Similarly, McBeath et al. [42] documented the China Environmental Education Centre's (CEEC) National Contest for Middle School Students on Water Scientific Invention. This competition, linked to the Stockholm Junior Water Prize, encourages students to apply scientific knowledge to address water challenges, fostering observation, problem-solving, and environmental participation [40].

Our study aligns with research highlighting the effectiveness of specific environmental education programs in China. The Green Community Project, for example, promotes green consumption and fosters environmentally conscious lifestyles [43]. National green communities, numbering over 236, serve as micro-models of sustainable development, contributing to national environmental goals and fostering human-environment harmony [41]. Additionally, the China BELL Project, an international initiative focused on environmental education, has demonstrated success through its multifaceted approach, including awareness raising, project expansion, and teacher training [41]. These examples showcase the positive influence of well-designed environmental education programs in promoting sustainable behaviors.

The Environmental Kuznets Curve (EKC) hypothesis suggests a link between economic development and environmental degradation, with pollution rising initially before technological advancements and environmental awareness leading to a decline [44]. Our study aligns with this concept. We observed that environmental education, potentially linked to increased spending on Sustainable Development Goal 4 (SDG 4), can foster innovation and responsible behavior changes. These changes can ultimately contribute to improved environmental outcomes in China, reinforcing education's crucial role in achieving the UN SDGs related to environmental sustainability. Existing initiatives like the 1000 Environment-Friendly Youth Ambassadors Action Program exemplify this point. The program aligns with China's environmental policy focus on energy conservation and emissions reduction, stimulating young volunteers' enthusiasm for environmental protection and encouraging active involvement [41,45,46]. Highlighting the potential of environmental education to mobilize young people and foster collective action, we propose scaling up such efforts to mobilize one million

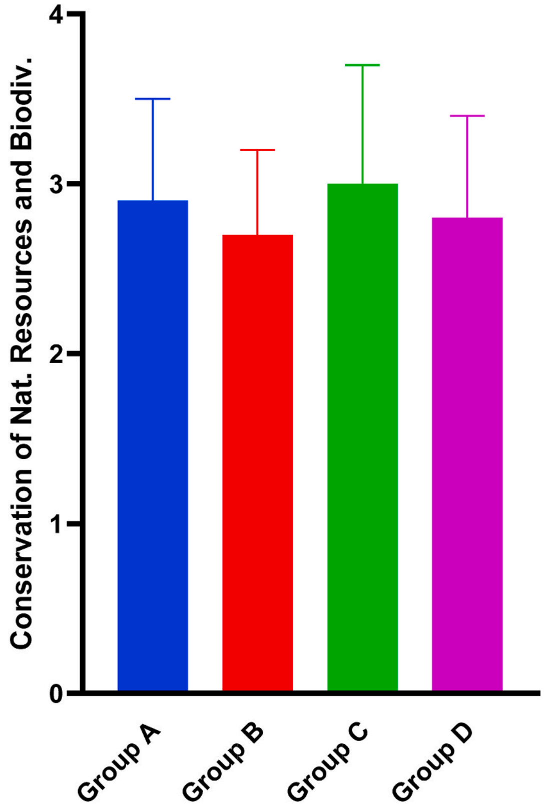

Fig. 4. Mean and SD for conservation of natural resources and biodiversity.

Table 5
Kruskal Wallis H test for Perceived Impact of Environmental Education on Conservation of Natural Resources and Biodiversity.

Group	N	Median Rank	
A	**200**	**450**	
B	**150**	**250**	
C	**180**	**520**	
D	**120**	**180**	
Statistic	**Value**	**df**	**Asymp. Sig. (2-tailed)**
Kruskal-Wallis H	**56.25**	**3**	**0.019**

individuals in energy conservation and environmental protection.

Environmental education has played a pivotal role in reducing energy consumption across various sectors, including Shenzhen's corporate and industrial landscape. Qu et al. [47] found that businesses and industrial parks in the region have integrated environmental education into their sustainability strategies, leading to the adoption of energy-efficient technologies and practices. This shift lowers energy use and enhances competitiveness and cost savings. Shenzhen's position as an electric vehicle (EV) industry leader is a testament to the influence of environmental education [48]. These programs have raised awareness about the environmental benefits of EVs, driving the widespread adoption of electric buses and charging infrastructure. The city has also championed eco-friendly transportation options, such as maglev trains and rapid railways, reducing carbon emissions and improving urban mobility. These findings were echoed by Song et al. [49], who showed that environmental education initiatives have played a vital role in promoting energy-efficient buses and developing sustainable railway systems in public transport. By educating the public about the environmental impacts of transportation choices and the benefits of low-emission options, Shenzhen has seen a significant shift towards more sustainable modes of travel [50].

Human capital fostered through education expenditure, is critical for environmental innovation [51]. An educated population with scientific knowledge and technical skills can develop environmentally friendly technologies in renewable energy, sustainable materials, and pollution control. Increased investment in education can cultivate a workforce capable of driving such innovation. Education is vital in raising environmental awareness and critical thinking skills. An environmentally literate population is more likely to understand environmental challenges, develop creative solutions, and adopt sustainable behaviors [52–54]. This highlights the interconnectedness of human capital, the environment, and education. Research suggests that human capital and renewable energy

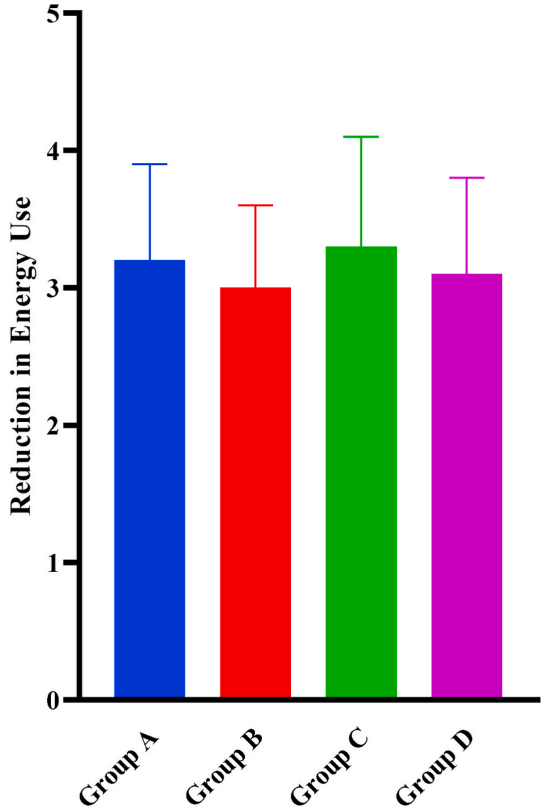

Fig. 5. Mean and SD for reduction in energy use.

Table 6
Regression analysis for reduction in energy use.

Predictor Variable	Estimate	SE	95 % CI Lower	95 % CI Upper	p-value
Group A	0.09	0.03	0.04	0.14	0.002
Group B	0.06	0.02	0.03	0.09	0.007
Group C	0.11	0.04	0.06	0.16	0.001
Group D	0.05	0.02	0.02	0.08	0.009

Table 7
Regression analysis for expanding public transit options.

Predictor Variable	Estimate	SE	95 % CI Lower	95 % CI Upper	p-value
Group A	0.14	0.05	0.08	0.20	0.001
Group B	0.10	0.04	0.05	0.15	0.003
Group C	0.17	0.06	0.10	0.24	0.001
Group D	0.12	0.04	0.07	0.17	0.001

consumption significantly impact China's environmental performance [52]. Similarly, studies show a positive influence of human capital on environmental quality, not just economic factors [53,54].

Studies in China support the positive influence of human capital on environmental sustainability. Lin et al. [55] found a correlation between innovative human capital and regional sustainability, suggesting that education fosters environmental awareness, problem-solving skills, and the ability to implement sustainable solutions. The impact extends beyond innovation. In middle-income countries, Choi et al. [56] demonstrated a positive association between environmental quality, human capital, and technological innovation. This suggests an educated population fosters public participation and advocacy for environmental protection, driving technological advancements and policy changes.

Our study strengthens the case for environmental education by quantifying its environmental benefits and highlighting its universality and the potential for targeted approaches. The positive outcomes observed across diverse participant groups – school-based, community-based, online, and corporate – demonstrate the broad applicability of environmental education. Our research goes beyond acknowledging this impact by providing evidence of measurable improvements in air/water quality, waste reduction, resource conservation, energy use, and public transit utilization. Furthermore, our findings suggest tailoring programs to specific contexts can enhance effectiveness. For example, online platforms might be ideal for promoting waste reduction strategies, while community programs could excel in fostering hands-on resource conservation practices. This highlights the need to move beyond a "one size fits all" approach and embrace targeted environmental education strategies.

4.1. Strengths and limitations

Our study offers valuable insights into the connection between environmental education programs and sustainable development practices in China. A key strength lies in its focus on measuring both environmental behaviors (waste reduction, energy use) and knowledge acquisition through the "Environmental Sustainability Assessment Survey" (ESAS). This allows for a more comprehensive understanding of the program's impact. However, limitations are also present. The study relies on self-reported data, which can be susceptible to bias as perceptions might not perfectly reflect reality [57]. Additionally, focusing on the past five years might not capture long-term behavioral changes influenced by past educational experiences. Future research could benefit from incorporating objective measures of environmental outcomes alongside surveys and examining program design variations in greater depth.

5. Conclusion

This study provided compelling evidence for the multifaceted benefits of environmental education in promoting sustainable practices in China. We observed significant improvements in air and water quality perceptions, with online programs demonstrating particular effectiveness. Waste reduction efforts also showed promise, especially in online programs, highlighting their potential. Additionally, environmental education played a crucial role in promoting energy conservation, which is evident in Shenzhen's transition towards sustainable transportation practices. These findings extend existing research by quantifying the positive impacts of environmental education on measurable environmental outcomes. Furthermore, our study offers valuable insights for policymakers. The effectiveness of targeted programs suggests the value of a multi-pronged approach. This includes mandating environmental education curricula across all educational levels, encouraging and supporting community-based environmental initiatives, investing in the development and accessibility of online environmental education platforms, and promoting collaboration between educational institutions and businesses to foster sustainable practices across sectors. By implementing these recommendations and learning from successful programs like the Green School Project and the National Water Invention Contest, China can further empower its citizens to contribute to environmental sustainability. The combined efforts of government policies, environmental NGOs, and educational initiatives hold immense potential for achieving long-term environmental progress and a harmonious relationship between humans and the environment.

Data availability

All data generated or analyzed during this study are included in this published article.

CRediT authorship contribution statement

Chanxi Yang: Investigation. **Zhongzheng Fang:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. ESAS Questionnaire

Introduction

Thank you for taking the time to participate in this survey. This survey aims to understand the impact of environmental education programs on sustainable development practices in China. Your responses are anonymous and confidential.

Demographics

- Age: (open-ended)
- Gender: (Select one)
  o Male
  o Female
  o Non-binary

o Prefer not to say

Environmental Education Experience/Measurement

- How important is environmental education in promoting sustainable development practices? (1–5)
- To what extent do you believe environmental education programs have increased your knowledge about environmental issues in China? (1–5)
- How likely are you to recommend an environmental education program to a friend or family member? (1–5)

Environmental Sustainability Practices

1. How knowledgeable do you feel about environmental issues facing China today? (1- Strongly Disagree; 5- Strongly Agree)
2. To what extent do you believe environmental education programs have influenced your understanding of environmental sustainability? (1- Not at all; 5- To a great extent)
3. How likely are you to participate in future environmental education programs or initiatives? (1- Very unlikely; 5- Very likely)

Environmental Sustainability Assessment (Please rate your agreement with the following statements)

Section 1: Improvements in Air and Water Quality

1. To what extent do you agree or disagree that environmental education has increased your awareness of air quality issues?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
2. How frequently do you engage in activities to reduce air pollution since participating in environmental education programs?
   - Never (1) - Rarely (2) - Occasionally (3) - Often (4) - Always (5)
3. Have you noticed improvements in the quality of the water sources in your community following environmental education initiatives?
   - Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)
4. Do you actively participate in water conservation efforts as a result of environmental education?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
5. Please rate the overall impact of environmental education on air and water quality in your area.
   - No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Section 2: Reductions in Waste Generation

1. How often do you practice waste reduction techniques learned through environmental education? Never (1) - Rarely (2) - Occasionally (3) - Often

   (4) - Always (5)

2. Has environmental education influenced your recycling habits? Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
3. Have you observed a decrease in waste generation within your household or community due to environmental education efforts? Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)
4. Do you actively participate in initiatives to reduce plastic usage after environmental education? Strongly Disagree (1) - Disagree (2) - Neutral

   (3) - Agree (4) - Strongly Agree (5)

5. Please rate the overall impact of environmental education on waste reduction in your area. No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Section 3: Conservation of Natural Resources

1. To what extent do you agree or disagree that environmental education has increased your awareness of the importance of natural resource conservation?

   Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)

2. How frequently do you engage in activities aimed at conserving natural resources since participating in environmental education programs?

Never (1) - Rarely (2) - Occasionally (3) - Often (4) - Always (5)

3. Have you noticed improvements in the conservation of local natural resources following environmental education initiatives?

   Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)

4. Do you actively participate in reforestation or habitat restoration efforts as a result of environmental education?

   Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)

5. Please rate the overall impact of environmental education on the conservation of natural resources in your area.

   No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Section 4: Protection of Biodiversity

1. To what extent do you agree or disagree that environmental education has increased your understanding of biodiversity conservation?

   Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)

2. How often do you participate in biodiversity conservation activities after taking part in environmental education programs?
   - Never (1) - Rarely (2) - Occasionally (3) - Often (4) - Always (5)
3. Have you observed an increase in the protection of local biodiversity due to environmental education efforts?
   - Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)
4. Do you actively engage in wildlife protection or habitat preservation as a result of environmental education?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
5. Please rate the overall impact of environmental education on the protection of biodiversity in your area.
   - No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Section 5: Reducing Energy Use

1. To what extent do you agree or disagree that environmental education has increased your understanding of energy conservation and efficiency?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
2. How often do you implement energy-saving practices following participation in environmental education programs?
   - Never (1) - Rarely (2) - Occasionally (3) - Often (4) - Always (5)
3. Have you observed a reduction in energy consumption within your household or community due to environmental education efforts?
   - Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)
4. Do you actively support renewable energy sources and energy-efficient technologies as a result of environmental education?
5. Please rate the overall impact of environmental education on reducing energy use in your area.
   - No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Section 6: Public Transit Options

1. How often do you choose public transportation over personal vehicles as a sustainable means of travel since participating in environmental education programs?
   - Never (1) - Rarely (2) - Occasionally (3) - Often (4) - Always (5)
2. Has environmental education influenced your preference for eco-friendly transportation options, such as public transit or carpooling?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
3. Have you observed an increase in the availability and accessibility of public transit options in your area due to environmental education initiatives?
   - Not at all (1) - Slightly (2) - Moderately (3) - Significantly (4) - Very significantly (5)
4. Do you actively promote the use of public transit and sustainable transportation methods as a result of environmental education?
   - Strongly Disagree (1) - Disagree (2) - Neutral (3) - Agree (4) - Strongly Agree (5)
5. Please rate the overall impact of environmental education on expanding public transit options in your area.
   - No Impact (1) - Minimal Impact (2) - Moderate Impact (3) - Significant Impact (4) - Very Significant Impact (5)

Additional Information

Is there anything else you would like to share about your views on environmental sustainability or your experience with environmental education programs? (open-ended).

Thank you!

References

[1] R. Pierrehumbert, There is no Plan B for dealing with the climate crisis, Bull. At. Sci. 75 (5) (2019 Sep 3) 215–221.
[2] N.K. Arora, Impact of climate change on agriculture production and its sustainable solutions, Environmental Sustainability 2 (2) (2019 Jun 1) 95–96.
[3] L. Chen, G. Msigwa, M. Yang, A.I. Osman, S. Fawzy, D.W. Rooney, P.S. Yap, Strategies to achieve a carbon neutral society: a review, Environ. Chem. Lett. 20 (4) (2022 Aug) 2277–2310.
[4] L. Rani, K. Thapa, N. Kanojia, N. Sharma, S. Singh, A.S. Grewal, A.L. Srivastav, J. Kaushal, An extensive review on the consequences of chemical pesticides on human health and environment, J. Clean. Prod. 283 (2021 Feb 10) 124657.
[5] S.N. Jorgenson, J.C. Stephens, B. White, Environmental education in transition: a critical review of recent climate change and energy education research, J. Environ. Educ. 50 (3) (2019 May 4) 160–171.
[6] K. Diprose, G. Valentine, R.M. Vanderbeck, C. Liu, K. McQuaid, Building common cause towards sustainable consumption: a cross-generational perspective, Environ. Plann.: nature and space 2 (2) (2019 Jun) 203–228.
[7] H.V. Nguyen, C.H. Nguyen, T.T. Hoang, Green consumption: closing the intention-behavior gap, Sustain. Dev. 27 (1) (2019 Jan) 118–129.
[8] L. Mei, W. Jun, Urban environment, green spaces, and mental health: an interdisciplinary investigation, Journal of Humanities and Applied Science Research 6 (4) (2023 Jul 9) 14–35.
[9] M.W. Zafar, M. Shahbaz, A. Sinha, T. Sengupta, Q. Qin, How renewable energy consumption contribute to environmental quality? The role of education in OECD countries, J. Clean. Prod. 268 (2020 Sep 20) 122149.
[10] H.J. Kooij, M. Oteman, S. Veenman, K. Sperling, D. Magnusson, J. Palm, F. Hvelplund, Between grassroots and treetops: community power and institutional dependence in the renewable energy sector in Denmark, Sweden, and The Netherlands, Energy Res. Social Sci. 37 (2018 Mar 1) 52–64.
[11] C. Liao, H. Li, Environmental education, knowledge, and high school students' intention toward separation of solid waste on campus, Int. J. Environ. Res. Publ. Health 16 (9) (2019 May) 1659.
[12] R. Dagiliūtė, G. Liobikienė, A. Minelgaitė, Sustainability at universities: students' perceptions from green and non-green universities, J. Clean. Prod. 181 (2018 Apr 20) 473–482.
[13] E. Udin, M. Lancaster, M. Fabian, A.A. Shanto, N. Papanikolopoulos, K. Blazev, et al., China dominates the clean energy market [Internet] [cited 2023 Sept 28]. Available from: https://www.gizchina.com/2023/09/04/china-dominates-clean-energy-market/, 2023.
[14] Mikhno I, Koval V, Shvets G, Garmatiuk O, Tamošiūnienė R. Green Economy in Sustainable Development and Improvement of Resource Efficiency.
[15] F. Green, A. Gambhir, Transitional assistance policies for just, equitable, and smooth low-carbon transitions: who, what, and how? Clim. Pol. 20 (8) (2020 Sep 13) 902–921.
[16] J.A. Leggett, The United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement: a Summary, vol. 2, UNFCC, New York, 2020 Jan 29.
[17] X. Zhao, X. Ma, B. Chen, Y. Shang, M. Song, Challenges toward carbon neutrality in China: strategies and countermeasures, Resour. Conserv. Recycl. 176 (2022 Jan 1) 105959.
[18] R. Owen, G. Brennan, F. Lyon, Enabling investment for the transition to a low carbon economy: government policy to finance early stage green innovation, Curr. Opin. Environ. Sustain. 31 (2018 Apr 1) 137–145.
[19] Boveroux O, Agrell PJ. " European Union Emissions Trading Scheme (EU ETS): Addressing Competitiveness and Carbon Leakage under Unilateral Climate Policy–Impact Analysis of the Implementation of a Border Carbon Adjustment (BCA).
[20] A. Iwan, K.K. Poon, The role of governments and green building councils in CITIES'TRANSFORMATION to become sustainable: case studies of Hong Kong (east) and vancouver (west), Sustainability and the City 67 (2018 Mar 28).
[21] W. Valley, H. Wittman, Beyond feeding the city: the multifunctionality of urban farming in Vancouver, BC. City, Culture, and Society 16 (2019 Mar 1) 36–44.
[22] P.M. Acosta Castellanos, A. Queiruga-Dios, A. Hernández Encinas, L.C. Acosta, Environmental education in environmental engineering: analysis of the situation in Colombia and Latin America, Sustainability 12 (18) (2020 Sep 4) 7239.
[23] A. Müller, H. Österlund, J. Marsalek, M. Viklander, The pollution conveyed by urban runoff: a review of sources, Sci. Total Environ. 709 (2020 Mar 20) 136125.
[24] X. Zheng, Y. Lu, J. Yuan, Y. Baninla, S. Zhang, N.C. Stenseth, D.O. Hessen, H. Tian, M. Obersteiner, D. Chen, Drivers of change in China's energy-related CO2 emissions, Proc. Natl. Acad. Sci. USA 117 (1) (2020 Jan 7) 29–36.
[25] H. Du, How is China managing its greenhouse gas emissions? [Internet], https://chinapower.csis.org/china-greenhouse-gas-emissions/, 2020. (Accessed 28 September 2023).
[26] M.H. Hansen, H. Li, R. Svarverud, Ecological civilization: interpreting the Chinese past, projecting the global future, Global Environ. Change 53 (2018 Nov 1) 195–203.
[27] K. Fang, Q. Zhang, J. Song, C. Yu, H. Zhang, H. Liu, How can national ETS affect carbon emissions and abatement costs? Evidence from the dual goals proposed by China's NDCs, Resour. Conserv. Recycl. 171 (2021 Aug 1) 105638.
[28] M.E. Krasny, Advancing Environmental Education Practice, Cornell University Press, 2020.
[29] H. Kopnina, Education for sustainable development (ESD): the turn away from 'environment'in environmental education?. InEnvironmental and Sustainability Education Policy Routledge, 2018 Dec 7, pp. 135–153.
[30] J. Gupta, R. Bakshi, Environmental Awareness and Sustainable Institutional Culture: Potent Mediators for Swachh Bharat Campaign, Available at: SSRN 4453737, 2023 May 19.
[31] J. Li, S. Zhou, W. Wei, J. Qi, Y. Li, B. Chen, N. Zhang, D. Guan, H. Qian, X. Wu, J. Miao, China's retrofitting measures in coal-fired power plants bring significant mercury-related health benefits, One Earth 3 (6) (2020 Dec 18) 777–787.
[32] Y. Feng, M. Ning, Y. Lei, Y. Sun, W. Liu, J. Wang, Defending blue sky in China: effectiveness of the "air pollution prevention and control action plan" on air quality improvements from 2013 to 2017, J. Environ. Manag. 252 (2019 Dec 15) 109603.
[33] J. Cheng, J. Su, T. Cui, X. Li, X. Dong, F. Sun, Y. Yang, D. Tong, Y. Zheng, Y. Li, J. Li, Dominant role of emission reduction in PM 2.5 air quality improvement in Beijing during 2013–2017: a model-based decomposition analysis, Atmos. Chem. Phys. 19 (9) (2019 May 9) 6125–6146.
[34] C. Gill, C. Lang, Learn to conserve: the effects of in-school energy education on at-home electricity consumption, Energy Pol. 118 (2018 Jul 1) 88–96.
[35] Q. Wang, M.P. Kwan, K. Zhou, J. Fan, Y. Wang, D. Zhan, The impacts of urbanization on fine particulate matter (PM2. 5) concentrations: empirical evidence from 135 countries worldwide, Environmental pollution 247 (2019) 989–998, https://doi.org/10.1016/j.envpol.2019.01.086.
[36] G. Li, Q. He, S. Shao, J. Cao, Environmental non-governmental organizations and urban environmental governance: evidence from China, J. Environ. Manag. 206 (2018) 1296–1307, https://doi.org/10.1016/j.jenvman.2017.09.076.
[37] A. Prüss-Üstün, J. Wolf, C. Corvalán, R. Bos, M. Neira, Preventing Disease through Healthy Environments: a Global Assessment of the Burden of Disease from Environmental Risks, World Health Organization, 2016.

[38] M. Zhang, X. Liu, X. Sun, W. Wang, The influence of multiple environmental regulations on haze pollution: evidence from China, Atmos. Pollut. Res. 11 (2020) 170–179.
[39] H. Zeng, G. Yang, J.C. Lee, Green Schools in China. Schooling for Sustainable Development in Chinese Communities: Experience with Younger Children, 2009, pp. 137–156.
[40] D.X. Zhao, B.J. He, F.Q. Meng, The green school project: a means of speeding up sustainable development? Geoforum 65 (2015 Oct 1) 310–313.
[41] Jiazhen HE. [Internet]. [cited 2023 September 28]. Available from: https://www.env.go.jp/earth/coop/temm/project/pdf/China%20Environmental%20Education%20for%20Sustainable%20Development%20and%20Introduction%20of%20Typical%20Cases.pdf.
[42] G.A. McBeath, J.H. McBeath, T. Qing, H. Yu, Environmental Education in China, Edward Elgar Publishing, 2014 Dec 31.
[43] H. Peng, G. Cheng, Z. Xu, Y. Yin, W. Xu, Social, economic, and ecological impacts of the "Grain for Green" project in China: a preliminary case in Zhangye, Northwest China, J. Environ. Manag. 85 (3) (2007 Nov 1) 774–784.
[44] S.M. de Bruyn, S.M. de Bruyn, The environmental Kuznets curve hypothesis, Economic Growth and the Environment: An Empirical Analysis (2000) 77–98.
[45] W. Liang, Changing climate? China's new Interest in global climate change negotiations, in: InChina's Environmental Crisis: Domestic and Global Political Impacts and Responses, vol. 15, Palgrave Macmillan US, New York, 2010 Oct, pp. 61–84.
[46] J. Xue, X. Xuan, China's green low-carbon development. Green Low-Carbon Development in China, 2013, pp. 1–30.
[47] Y. Qu, Y. Liu, R.R. Nayak, M. Li, Sustainable development of eco-industrial parks in China: effects of managers' environmental awareness on the relationships between practice and performance, J. Clean. Prod. 87 (2015 Jan 15) 328–338.
[48] L. Zhu, P. Wang, Q. Zhang, Indirect network effects in China's electric vehicle diffusion under phasing out subsidies, Appl. Energy 251 (2019 Oct 1) 113350.
[49] Q. Song, J. Li, H. Duan, D. Yu, Z. Wang, Towards to sustainable energy-efficient city: a case study of Macau, Renew. Sustain. Energy Rev. 75 (2017 Aug 1) 504–514.
[50] X. Tan, T. Tu, B. Gu, Y. Zeng, Scenario simulation of CO2 emissions from light-duty passenger vehicles under land use-transport planning: a case of Shenzhen International Low Carbon City, Sustain. Cities Soc. 75 (2021 Dec 1) 103266.
[51] F.A. Twum, X. Long, M. Salman, C.N. Mensah, W.A. Kankam, A.K. Tachie, The influence of technological innovation and human capital on environmental efficiency among different regions in Asia-Pacific, Environ. Sci. Pollut. Control Ser. 28 (2021 Apr) 17119–17131.
[52] S.A. Sarkodie, S. Adams, P.A. Owusu, T. Leirvik, I. Ozturk, Mitigating degradation and emissions in China: the role of environmental sustainability, human capital, and renewable energy, Sci. Total Environ. 719 (2020 Jun 1) 137530.
[53] Z. Ahmed, M.M. Asghar, M.N. Malik, K. Nawaz, Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China, Resour. Pol. 67 (2020 Aug 1) 101677.
[54] L. Ni, S.F. Ahmad, T.O. Alshammari, H. Liang, G. Alsanie, M. Irshad, R. Alyafi-AlZahri, R.H. BinSaeed, M.H. Al-Abyadh, S.M. Bakir, A.Y. Ayassrah, The role of environmental regulation and green human capital towards sustainable development: the mediating role of green innovation and industry upgradation, J. Clean. Prod. 421 (2023 Oct 1) 138497.
[55] X. Lin, Z. Ahmed, X. Jiang, U.K. Pata, Evaluating the link between innovative human capital and regional sustainable development: empirical evidence from China, Environ. Sci. Pollut. Control Ser. 30 (43) (2023 Sep) 97386–97403.
[56] J.Y. Choi, D.B. Han, The links between environmental innovation and environmental performance: evidence for high-and middle-income countries, Sustainability 10 (7) (2018 Jun 25) 2157.
[57] P. Prendergast, S. Pearson-Merkowitz, C. Lang, The individual determinants of support for open space bond referendums, Land Use Pol. 82 (2019 Mar 1) 258–268.