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Waste-to-energy and its asymmetric impact on ecological footprint: implications for environmental sustainability

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As global populations grow and economies expand, the surge in municipal solid waste presents a significant challenge to ecological sustainability. Waste management involves a critical trade-off between traditional methods, such as landfilling and combustion, and the alternative of waste-to-energy (WtE) systems, which convert waste into usable energy. However, the environmental impact of these methods is not uniform, demonstrating an asymmetric effect depending on the strategy employed. This study investigates the asymmetric relationship between waste-to-energy and ecological footprints in China and the United States from 1980 to 2021, using advanced econometric techniques such as NARDL and MT-NARDL. Our findings highlight the potential of WtE systems in mitigating ecological footprints, offering a promising solution for sustainability in both countries. We recommend a dual-pronged strategy incorporating financial support to WtE plants alongside Feed-in Tariff (FIT) schemes. This will ensure their viability and foster an environment where these initiatives can thrive, ultimately contributing to a greener future.

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Introduction

The Paris Agreement, adopted by 178 countries in 2015, has catalyzed extensive multidisciplinary research (Husaini et al., 2021). A significant portion of research in the energy and environmental fields has focused on the increasing role of renewable energy in enhancing environmental sustainability (Lean and Smith, 2010; Husaini and Lean, 2022). Numerous studies, including those by Hammoudeh et al. (2015), Balaguer and Cantavella (2016), Zoundi (2017), and Husaini et al. (2021), have highlighted the price factor as a barrier to environmental sustainability. Meanwhile, research by Zhao et al. (2022) and Bai et al. (2023) has explored how changes in economic structures can enhance environmental sustainability. However, it is crucial to recognize that municipal solid waste also contributes significantly to environmental degradation (Downs et al., 2019). Overlooking this aspect misses a crucial component of environmental sustainability efforts. Thus, waste management plays a vital role in mitigating the harmful impacts of municipal solid waste on the environment (Zhang et al., 2022).

In this study, the ecological footprint (EFP) has been employed as a comprehensive indicator of environmental pressure. It was originally developed by Wackernagel and Rees (1996) and measures the biologically productive land and water area required to supply the resources consumed by a population and to assimilate the waste it generates. Expressed in global hectares (gha), EFP provides a broader and more holistic measure of environmental sustainability than single-pollutant indicators such as CO₂ emissions, since it incorporates factors, such as energy use, food consumption, timber extraction, built-up land, and waste absorption requirements (Zoundi, 2017; Nathaniel, 2021). The literature further emphasizes the importance of EFP as a proxy for environmental sustainability, as global ecological footprints have expanded from 7.0 billion gha in 1961 to over 20.6 billion gha in 2014, reflecting the increasing strain on natural ecosystems (Raghutla and Kolati, 2023). Accordingly, EFP has become a widely used benchmark for assessing ecological outcomes in empirical energy–environment studies.

Due to the increasing global production of trash, waste management has become a concern worldwide (Kahhat et al., 2008). Annually, ~2.01 billion tons of waste are produced, a figure that is continually rising. On average, each person generates about 0.74 kg (1.63 pounds) of municipal solid waste per day globally (Kumar et al., 2023). The ecological footprint increases due to improper waste disposal, as greenhouse gases are emitted into the atmosphere (Kasper, 2013; Buzby, 2022). This is particularly true for municipal solid waste, which releases carbon dioxide and other greenhouse gases into the atmosphere when burned (Anshassi et al., 2021).

Municipalities worldwide are facing an unprecedented surge in municipal solid waste generation due to surging populations and increased consumption. Waste-to-energy (WtE) technology is a promising solution to address both energy demands and waste management challenges globally (Pheakdey et al., 2023; Karmakar et al., 2023; Chien et al., 2023; Tsui and Wong, 2019). The symbiotic relationship between environmental stewardship and energy sufficiency underscores its significance in the modern era (Anshassi et al., 2021). However, the implementation of waste-to-energy involves complex factors and numerous stakeholders (Lisbona et al., 2023).

Waste-to-energy is a dynamic approach to mitigating reliance on traditional energy sources while simultaneously addressing the growing waste dilemma (Okedu et al., 2022). The continual evolution of municipal solid waste processing methods and pollution abatement technologies has positioned WtE as a viable avenue for sustainable energy production (Lu et al., 2023). Nevertheless, challenges loom large, as mismanagement of waste

poses significant environmental risks, with landfills serving as potent sources of pollution (Wang et al., 2015). Similarly, energy generation through waste incineration presents environmental quandaries, primarily in terms of greenhouse gas emissions (Istrate et al., 2023; Mata-Lima et al., 2021). Mitigating these impacts necessitates concerted efforts such as waste reduction and robust recycling initiatives (Jin et al., 2021).

Moreover, the transition to waste-to-energy has been hampered by the requirement for advanced technology to ensure clean and environmentally friendly energy generation (Zhang et al., 2015). This necessitates substantial investment in high-tech solutions, leading to high marginal costs. Thus, genuine environmental compatibility in waste-to-energy operations demands continual innovation and the adoption of state-of-the-art technologies, further amplifying the financial burden of such ventures.

Given the significant negative impact of municipal solid waste on ecosystems, it stands as a major contributor to ecological footprints. Ineffective waste management exacerbates pollution, leads to habitat degradation, and depletes natural resources (Kahhat, 2008). Waste reduction and judicious resource utilization can mitigate environmental impacts and pave the way towards a more sustainable future.

A comprehensive and forward-looking perspective on emissions stemming from waste-to-energy processes is imperative in our quest for achieving carbon neutrality (Song et al., 2023; Kwon et al., 2023). The complexity of the waste-to-energy conversion process has been the subject of countless research projects, yet there is still a glaring knowledge vacuum about the broader economic ramifications of this technology. The waste-to-energy processes can be supported by a better understanding of the waste-energy-economy nexus. While research has already shown how waste, energy, and the economy each contribute to carbon neutrality, there is still little knowledge of how these three factors interact in the context of long-term carbon neutrality (Jia and Lin, 2021). This calls for deliberate efforts to examine the environmental impact of waste-to-energy technologies.

This study aims to discern and evaluate the influence of waste-to-energy practices on the ecological footprint of two leading countries in the field, namely the United States and China. This study aims to empirically assess the role of waste-to-energy (WtE) in shaping environmental sustainability, with a particular focus on its impact on the ecological footprint (EFP). The first objective is to estimate the asymmetric effects of WtE on the ecological footprint in China and the United States, respectively. The study thus seeks to determine whether expansions in WtE capacity improve ecological outcomes more strongly than reductions in WtE capacity worsen them, thereby revealing potential asymmetries in the WtE–EFP nexus. The second objective is to examine the threshold effects of WtE on ecological footprint outcomes, assessing whether the ecological benefits of WtE become more pronounced only after reaching certain levels of adoption. This analysis provides insights into the scale at which WtE shifts from a modest contribution to a more transformative impact on environmental sustainability.

The contributions of this study include, first, that it takes China and the United States as its samples. The similarity of these two countries is that both have the largest populations in the world. Essentially, a larger population generates more municipal solid waste, which increases landfill (Hoornweg et al., 2013). Hence, waste management is a critical issue in both countries. Due to this, both China and the United States have taken advantage of establishing more waste-to-energy (WtE) plants. The WtE market is growing, having been valued at \$35.1 billion in 2019, and it is forecast to reach \$50.1 billion by 2027. Hence, this study provides robust projections, based on advanced econometric techniques, of

the potential impact of WtE expansion on environmental quality improvement in China and the United States.

The contradiction between China and the United States is that, according to the World Bank classification, China still holds the status of a developing country, while the United States leads the developed countries of the world. From the perspective of waste management policy, undoubtedly, as a developed country, the United States has a very systematic structure in organizing the problem of waste combustion (Kahhat et al., 2008; Ali et al., 2023). While the United States has a systematic approach to municipal solid waste management, China lacks organized waste management strategies (Kahhat et al., 2008; Ali et al., 2023). Hence, this characteristic determines the different behaviors of WtE in contributing to environmental quality improvement. By comparing China (a developing country) and the United States (a developed country), the study offers new insights into how WtE operates under different developmental contexts, thereby providing comparative evidence that extends beyond single-country analyses.

Another interesting aspect prompting the study of WtE in these two countries is the fluctuating trend in its generation over time. Although the general trend is declining, both countries have experienced fluctuations, occasionally showing an upward trend. This warrants further investigation, particularly regarding its impact on the environment. The International Energy Agency has generally estimated that WtE plants reduce 2000 pounds of garbage to ash, weighing about 300–600 pounds, decreasing the volume of waste by about 87%. Hence, channeling waste for energy or other alternatives in combination is an option that policymakers should emphasize for a sustainable environmental future. It clearly shows that these two countries have no clear direction for the development of WtE. Since this study takes the perspective of asymmetry, the output of this study will help policymakers to understand the implications of choosing or not choosing to enhance WtE as a pathway for environmental quality improvement.

Second, this study contributes by extending the limited body of research that applies nonlinear time series approaches to municipal waste-to-energy analysis. Combusting municipal waste, whether in landfills or for energy generation, is a pivotal strategy for waste management and environmental sustainability. Landfill combustion carries higher environmental risks compared to energy generation, particularly when advanced emission-minimizing technologies are employed. This suggests an asymmetric effect, where the environmental impacts of waste-to-energy vary depending on the scale and sophistication of combustion (Guoyan et al., 2021).

Furthermore, the literature shows that significant positive impacts of waste-to-energy on environmental quality may only be realized beyond a certain production threshold (Turner et al., 2015; Aich and Ghosh, 2016; Lee et al., 2016; Razaq et al., 2021). Below this threshold, waste-to-energy initiatives may lack the scale necessary to effectively address ecological challenges. Thus, achieving optimal utilization of waste-to-energy is crucial for realizing its potential benefits and promoting environmental sustainability.

By applying advanced nonlinear time-series methods (NARDL and MT-NARDL), this study is among the first to capture both asymmetric impacts (increases vs. decreases in WtE) and threshold effects (ecological benefits that strengthen once WtE reaches critical levels of deployment). While nonlinear models have been widely used in environmental and energy research, applications to the WtE–ecological footprint nexus remain scarce, and existing studies have largely relied on linear frameworks of renewable energy in aggregate (Sharma et al., 2021; Rahmane et al., 2021; Zhang et al., 2022; AlNemer et al., 2023; Destek and

Aslan, 2020). Our study addresses this gap by integrating NARDL and MT-NARDL approaches and demonstrates why nonlinear estimation is essential for capturing the full environmental effects of WtE.

Third, this study looks specifically at the role of waste-to-energy (WtE) as one of the renewable energy sources affecting the ecological footprint. Different from Sharma et al. (2021) and Rahmane et al. (2021), which focus on total renewable energy consumption, and from Zhang et al. (2022), AlNemer et al. (2023), and Destek and Aslan (2020), which exclude WtE sources entirely, our study isolates the impact of WtE on environmental quality. Hence, the current literature fails to adequately consider the potential of WtE in influencing ecological sustainability. While prior research has examined renewable energy in aggregate, few studies have specifically identified WtE as a separate renewable source. By focusing explicitly on WtE, we address this gap in the literature, where its unique role has often been overlooked (cf. Sharma et al., 2021; Rahmane et al., 2021; Zhang et al., 2022; AlNemer et al., 2023; Destek and Aslan, 2020). This distinction is critical, as WtE differs substantially from other renewable energy sources in terms of both technological features and ecological implications. Therefore, its contributions to environmental quality improvement warrant independent analysis.

This paper is organized as follows. Section “The waste-to-energy industry: global developments and country evidence from China and the United States” provides a discussion on the overview of Waste-to-Energy in China and the United States. Section “Model and methodology and Data” explains model specification, methodological strategy, and data. Section “Empirical results and discussion” focuses on presenting the empirical results and discussion. Lastly, the section “Conclusion and operational applicability” concludes the whole paper and makes policy recommendations.

The waste-to-energy industry: global developments and country evidence from China and the United States

Before exploring the complexities of the waste-to-energy industry, it is essential to understand the taxonomy of waste that contributes to this transformative process. A typical municipal solid waste stream includes a diverse range of materials, from biodegradable organics to non-recyclable plastics and paper products. Notably, ~44% of this waste is organic, consisting of biodegradable materials such as food scraps, yard waste, and paper, as illustrated in Fig. 1. Each component has unique potential for energy recovery through various waste-to-energy (WtE) processes.

The principles of waste management, often represented by the waste pyramid and integrated waste management approaches as shown in Fig. 2, have been widely recognized as essential guidelines for addressing the global challenges of waste and its impact on the environment.

A paramount challenge we face today is the need to find sustainable solutions to mitigate environmental pollution and meet global energy demands. In this context, reducing municipal solid waste generation at its source proves to be a pivotal and highly effective strategy. By minimizing waste production from the outset, we can significantly relieve the burden on waste management systems and reduce the environmental footprint (Peng et al., 2023).

To further enhance our waste management efforts, converting municipal solid waste into alternative energy sources, such as waste-to-energy technologies, is not simply desirable but actually imperative. These technologies provide a promising avenue to repurpose waste materials while simultaneously addressing the

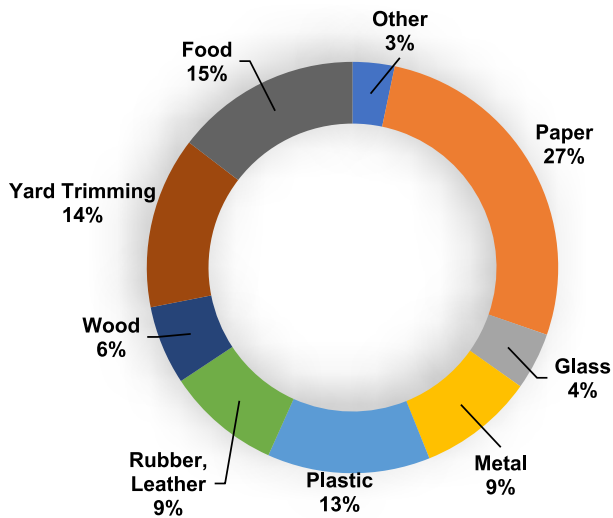


Fig. 1 MSW composition.

issues of waste disposal and energy generation. However, effectively reducing municipal solid waste remains a complex task demanding multifaceted solutions (Varjani et al., 2022).

Figure 3 depicts the potential applications of municipal solid waste in energy production, electricity generation, and even as a source for fertilizer production. These diverse applications highlight the importance of exploring innovative approaches to maximize the value and sustainability of municipal solid waste, contributing to both environmental preservation and the evolution of the energy sector (Tan et al., 2015).

Examining the global landscape of waste-to-energy, as illustrated in Fig. 4, it is evident that the United States and China are dominant in this sector. According to the latest data up to 2021 (Statista, 2023), these two countries together generate a remarkable total of over 480 million metric tons of municipal solid waste (MSW) annually. In the United States, characterized by high consumption and urbanization, an impressive 265 million tons of municipal waste are produced each year. On the other hand, China, driven by its large population and rapid urban development, produces ~215 million tons of municipal waste annually. These figures underscore the significant challenges both nations

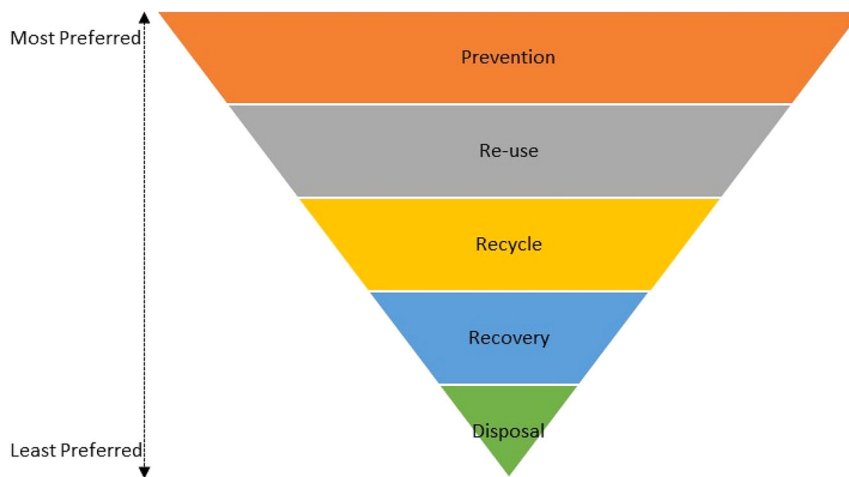


Fig. 2 Municipal waste management pyramid.

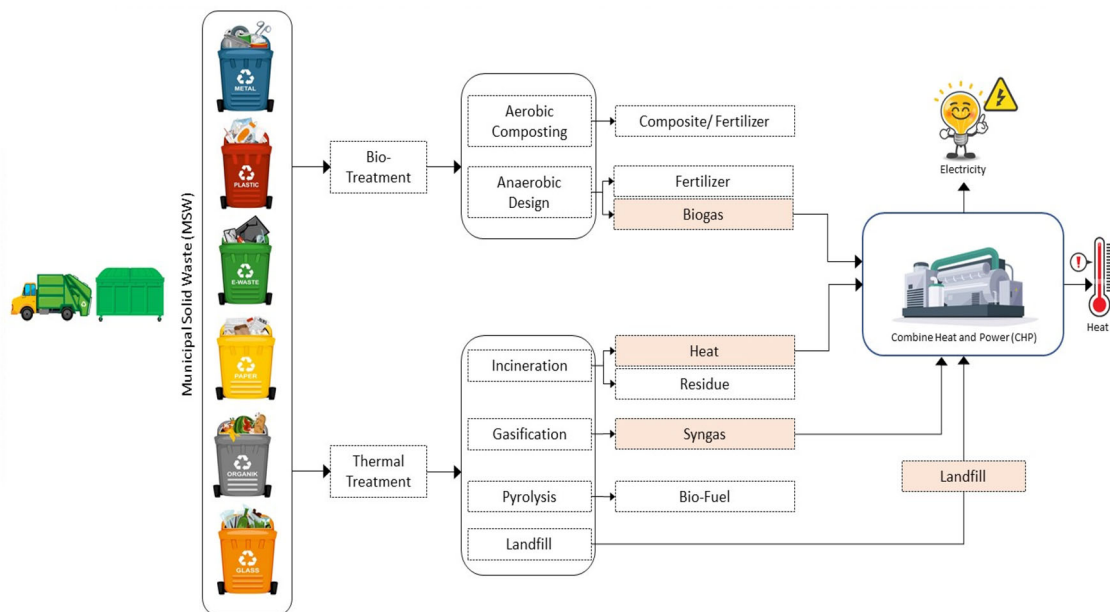


Fig. 3 Municipal solid waste application process.

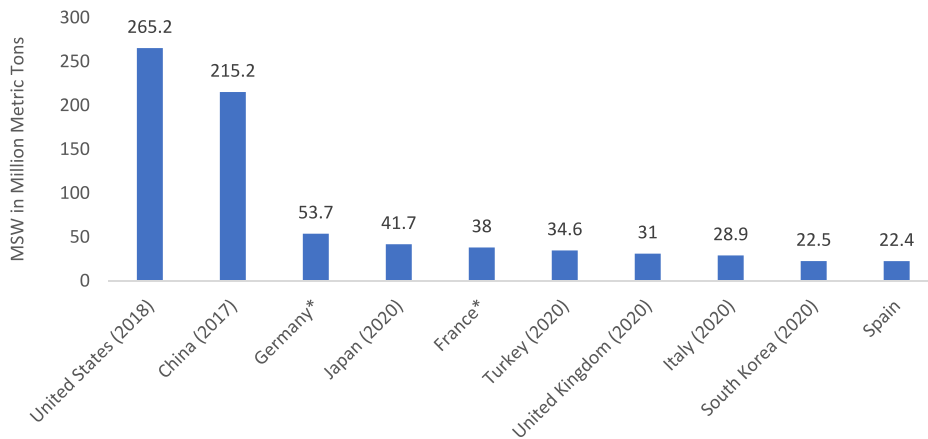


Fig. 4 World's leading countries in MSW production. Source: Statista (2023).

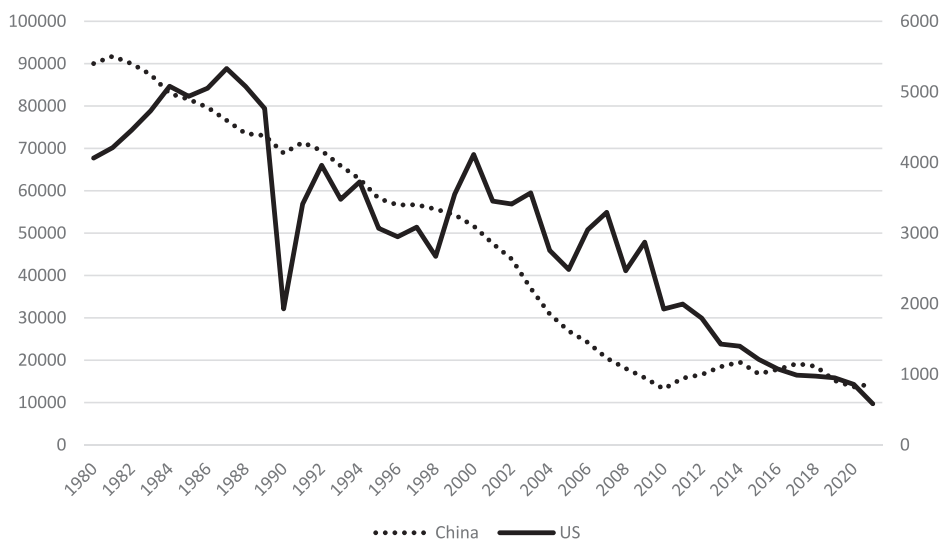


Fig. 5 Waste-to-Energy Generation (KToe) in China and the United States, 1980–2021. Source: IEEJ and CEIC Database.

face in effectively managing their waste streams. Addressing these challenges requires not only robust waste management infrastructures but also innovative strategies aimed at reducing waste generation and promoting sustainable consumption patterns.

Figure 5 presents a comparison of waste-to-energy (WtE) production trends in China and the United States from 1980 to 2022. It is clear that China’s WtE plants produce more energy than those in the United States. However, China has experienced fluctuating trends in WtE production over the past few decades, displaying a mix of both increasing and decreasing patterns. Notably, from 1982 to 2010, there was a significant decline, with an average annual decrease of 6.31%. Despite this, certain periods within this timeframe, such as 1991–1992, showed growth with an average annual increase of 0.47%. Since 2010, there has been a general upward trend, although production levels remain relatively low compared to previous decades. 2011–2021 saw a modest rise, with an average yearly growth rate of 1.41%. Despite this growth, statistical analysis indicates an average annual decline of -4.04% in WtE production from 1980 to 2021. Presently, China operates 300 WtE plants, with additional facilities under construction or in planning stages (General Kinematics, 2017). The government aims to process nearly a third of the country’s waste through these plants by 2030 (Standaert, 2017). Periods of decline in China were closely linked to shifting government priorities and growing public opposition to incineration projects in urban areas, while the more recent upward trend

reflects renewed large-scale investments and stricter waste management targets. This has repositioned WtE as a strategic tool within China’s circular economy agenda (Kurniawan et al., 2022).

In contrast, the United States has shown a more dynamic trend in WtE generation. From 1981 to 1987 and again from 1991 to 2013, there was a noticeable upward trend, with average annual increases of 4.01% and 1.02%, respectively. Conversely, there were declines from 1988 to 1990 and from 2014 to 2021, with average annual decreases of 23.48% and 10.06%, respectively. Overall, WtE growth in the U.S. averaged -2.43% per year from 1980 to 2021. These fluctuations largely stem from economic and regulatory factors. For example, low landfill tipping fees in many states reduced the competitiveness of WtE relative to landfilling, while evolving emissions standards and state-level permitting restrictions have also shaped plant operations and expansion (Themelis and Ulloa, 2007; U.S. Environmental Protection Agency, 2023).

WtE production in China and the United States thus reveals complex scenarios. Although China typically produces more WtE, both countries have seen fluctuating trends over the years. Notably, the United States has experienced significant periods of increase, despite an overall decreasing trend. This divergence underscores how institutional, economic, and societal contexts critically shape the WtE sector. In China, centralized investment drives growth despite public opposition, while in the US, market incentives and regulatory pressures have produced more

volatility. These insights highlight the need for further empirical research to understand the environmental impacts associated with fluctuations in WtE production. Such research can guide policymakers in integrating WtE systems into circular economic frameworks, thus promoting a sustainable future that harmonizes energy needs with environmental conservation. Additionally, these findings can provide valuable lessons for other countries planning to develop WtE ecosystems, aiding informed decision-making and fostering global sustainability efforts.

Model and methodology

We have adopted the environmental Kuznets curve (EKC) as the theoretical framework for this study. The ecological footprint (EFP) is the endogenous variable, serving as a proxy for environmental outcomes, while Waste-to-Energy (WtE) represents the core explanatory variable. Following the EKC hypothesis (Grossman and Krueger, 1995; Stern, 2004; Dogan and Seker, 2016), we include both GDP and its squared term (GDP^2) in order to capture the potential non-linear, inverted U-shaped relationship between economic development and environmental quality. To mitigate the risk of omitted variable bias, we have furthered incorporate financial development (FD) and foreign direct investment inflows (FDI) as control variables, consistent with the approaches of Shahbaz et al. (2013) and Al-Mulali et al. (2015). This specification will enable us to evaluate how WtE initiatives interact with income, financial development, and investment dynamics in influencing ecological outcomes. Accordingly, our proposed model is structured as in Eq. (1) as follows:

$$EFP_t = \beta_0 + \beta_1 WtE_t + \beta_2 GDP_t + \beta_3 GDP_t^2 + \beta_4 FID_t + \beta_5 FDI_t + \varepsilon_t \quad (1)$$

where

- EFP = ecological footprint (gha)
- WtE = energy generated by waste (KTeo)
- GDP = gross domestic product constant in year 2015 (USD)
- FID = domestic credit to the private sector constant in year 2015 (USD)
- FDI = foreign direct investment inflows constant in the year 2015 (USD)

The core explanatory variable in this study is waste-to-energy (WtE), which is measured as the energy generated from municipal solid waste combustion. By converting waste into electricity and reducing landfill reliance, WtE is generally interpreted as environmentally beneficial, since it lowers the ecological footprint by mitigating methane emissions and land-use pressures (Brunner and Rechberger, 2015). In this context, a negative coefficient indicates that rising WtE reduces ecological footprint, while a positive coefficient would suggest the opposite. WtE is central to our analysis, because the study examines whether its effects are asymmetric (increases vs. decreases), and whether the benefits strengthen at the higher thresholds of adoption.

Economic expansion is represented by gross domestic product (GDP) and its squared term (GDP^2), which are included under the framework of the environmental Kuznets curve (EKC). The EKC hypothesis suggests that the relationship between development and environmental degradation follows an inverted U-shape. GDP and GDP^2 have therefore been widely used to test the EKC hypothesis in various contexts (Al-Mulali et al., 2015; Ahmad and Du, 2017; Appiah, 2016). In this study, the inclusion of GDP and GDP^2 not only validates the EKC framework but also serves to link WtE impacts with stages of development. This is particularly relevant for the comparative analysis of China and

the United States, enabling us to assess whether the WtE–EFP relationship actually varies across different stages of economic development.

Financial development (FD) is also included as a control variable, given its potential influence on ecological outcomes. Financial development enhances competitiveness in capital markets and facilitates access to loans, thereby promoting industrialization and expanding business opportunities. In the initial stages, this process tends to increase energy demand and carbon-intensive activities, which may heighten environmental degradation (Cheng et al., 2020; Nathaniel, 2021). However, as financial systems mature, they can contribute to environmental improvements by encouraging investment in energy-efficient and cleaner technologies, leading to a shift toward sustainability (Sinha et al., 2020). In this context, FD may exhibit both positive and negative effects, depending on the stage of financial maturity. Including FD in our model ensures that the estimated effects of WtE are not confounded by variations in domestic financing, thereby isolating the ecological contribution of WtE while also accounting for broader financial dynamics.

Finally, foreign direct investment (FDI) inflows are employed as an additional explanatory variable. Unlike gross capital formation, FDI inflows are less likely to generate multicollinearity problems with GDP, making them a more suitable proxy for capturing capital effects. The theoretical relationship between FDI and the environment can be explained through two competing hypotheses. The pollution haven hypothesis argues that multinational corporations may relocate pollution-intensive activities to countries with lax environmental regulations, effectively transferring environmental degradation to host economies (Copeland and Taylor, 1994; Walter and Ugelow, 1979). In contrast, the pollution halo hypothesis suggests that foreign firms can contribute positively by introducing cleaner technologies and more efficient production processes to host countries (Kim and Adilov, 2011). Based on the experience of many developing nations, we anticipate a positive association between FDI inflows and ecological footprint, which is consistent with the pollution haven perspective. By incorporating FDI into our model, we have controlled for the influence of globalization on environmental outcomes and ensured that the estimated WtE–EFP relationship is both robust and not biased by external capital dynamics.

Pal and Mitra (2019) have argued that symmetric behavior does not always reflect real-world phenomena. As previously discussed, waste-to-energy (WtE) initiatives can affect environmental quality from various perspectives and angles. Consequently, a nonlinear approach is required to accurately assess these effects.

The concept of “asymmetric impact” refers to the idea that positive and negative changes in an explanatory variable may have different magnitudes or directions of effect on the dependent variable. In the context of this study, increases and decreases in waste-to-energy (WtE) generation may not have commensurate impacts on the ecological footprint. For instance, expanding WtE capacity could reduce ecological pressure significantly, while reductions in WtE capacity might increase the ecological footprint more sharply. Capturing such asymmetric dynamics requires nonlinear approaches, which decompose the explanatory variable into positive and negative partial sums (Shin et al., 2014; Pal and Mitra, 2019).

To meet our first objective, we utilize the nonlinear autoregressive distributed lag (NARDL) model. The NARDL framework allows us to evaluate whether a symmetric or an asymmetric model is more appropriate for exploring the impact of the exogenous variable (WtE) on the endogenous variable (EFP). We have applied the NARDL model to specifically determine the asymmetric effects of WtE on EFP, enabling us to understand

how WtE influences EFP during periods of increase and decrease. Based on Eq. (1), the NARDL model is as shown in Eq. (2) as follows:

$$EFP_t = \beta_0 + \beta_1 WtE_t^+ + \beta_2 WtE_t^- + \beta_3 GDP_t + \beta_4 FID_t + \beta_5 FDI_t + \varepsilon_t \tag{2}$$

The asymmetric impact of WtE can be captured by adding the positive change of WtE (WtE_t^+) and the negative change of WtE (WtE_t^-). The WtE_t^+ and WtE_t^- are functions of partial sums of the positive and negative changes in WtE, respectively. We formulate WtE_t^+ and WtE_t^- as follows:

$$WtE_t^+ = \sum_{i=1}^t \Delta WtE_t^+ = \sum_{i=1}^t \max(\Delta WtE_t, 0)$$

$$WtE_t^- = \sum_{i=1}^t \Delta WtE_t^- = \sum_{i=1}^t \min(\Delta WtE_t, 0)$$

Nevertheless, the NARDL model does not provide detailed information about a regressor’s behavior at specific threshold levels (Pal and Mitra, 2019). To align with our second objective, we have enhanced our analysis by employing the multi-threshold nonlinear ARDL (MT-NARDL) model to examine how waste-to-energy (WtE) influences the ecological footprint (EFP) at distinct threshold levels of WtE. In this approach, WtE is divided into different quantiles to assess the asymmetric effects of the regressor. Variations in WtE, whether high or low, are likely to impact EFP differently. This method enables us to observe and differentiate the behavior of WtE across each quantile.

In line with standard empirical practice, we have adopted the 25th, 50th, and 75th percentiles of WtE as thresholds in the MT-NARDL model. These quantiles provide sufficient variation to capture the full spectrum of WtE development, while avoiding over-parameterization that could arise from using too many thresholds, such as terciles or deciles, which may strain the degrees of freedom and reduce model efficiency (Shin et al., 2014; Pal and Mitra, 2019). To implement this asymmetric analysis, we configured the MT-NARDL model by segmenting the WtE series into quintiles, thereby creating four partial sum series:

$$WtE_t = WtE_t(\omega_1) + WtE_t(\omega_2) + WtE_t(\omega_3) + WtE_t(\omega_4)$$

$WtE_t(\omega_1)$, $WtE_t(\omega_2)$, $WtE_t(\omega_3)$ and $WtE_t(\omega_4)$ are four partial sums where the 25th, 50th, 75th, and 100th quintiles of ES fluctuations are set as three thresholds represented by τ_{25} , τ_{50} , and τ_{75} , respectively, and they are derived as follows:

$$WtE_t(\omega_1) = \sum_{i=1}^t \Delta WtE_t(\omega_1) = \sum_{i=1}^t \Delta WtE_t I\{\Delta WtE_t \leq \tau_{25}\} \tag{3}$$

$$WtE_t(\omega_2) = \sum_{i=1}^t \Delta WtE_t(\omega_2) = \sum_{i=1}^t \Delta WtE_t I\{\tau_{25} < \Delta WtE_t \leq \tau_{50}\} \tag{4}$$

$$WtE_t(\omega_3) = \sum_{i=1}^t \Delta WtE_t(\omega_3) = \sum_{i=1}^t \Delta WtE_t I\{\tau_{50} < \Delta WtE_t \leq \tau_{75}\} \tag{5}$$

$$WtE_t(\omega_4) = \sum_{i=1}^t \Delta WtE_t(\omega_4) = \sum_{i=1}^t \Delta WtE_t I\{\Delta WtE_t > \tau_{75}\} \tag{6}$$

where $I\{\cdot\}$ is an indicator function with value 1 given the conditions expressed within $\{\cdot\}$ in Eqs. (3)–(6) are satisfied, otherwise it is zero. The split of WtE in quintiles is expressed in an MT-NARDL framework as in Eq. (7) as follows:

$$\begin{aligned} \Delta EFP_t = & \alpha_1 + \sum_{i=1}^p \delta_i \Delta EFP_{t-i} + \sum_{j=0}^q \sum_{i=0}^n \Omega_i WtE_{t-j}(\omega_j) + \sum_{l=0}^r \rho_l \Delta GDP_{t-k} \\ & + \sum_{m=0}^s \lambda_m \Delta GDP_{t-l}^2 + \sum_{m=0}^u \theta_m \Delta FID + \sum_{m=0}^v \theta_p \Delta FDI \\ & + \pi_1 EFP_{t-1} + \pi_2 WtE_{t-1}(\omega_j) + \pi_3 GDP_{t-1} + \pi_4 GDP_{t-1}^2 \\ & + \pi_5 FID_{t-1} + \pi_6 FDI_{t-1} + \varepsilon_t \end{aligned} \tag{7}$$

We can test cointegration among the long-run variables of Eq. (7) following the null hypothesis $H_0: \pi_1 = \pi_2 = \pi_3 = \pi_4 = \pi_5 = \pi_6 = 0$. We use the critical values provided by Pesaran et al. (2001) to perform the bound tests. NARDL and MT-NARDL deliver a reliable quantitative outcome that could potentially be deployed in the real world.

Data

The dataset employed in this study covers the period 1980–2021 for both China and the United States. The dependent variable, ecological footprint (EFP), has been sourced from the BP Statistical Review and expressed in global hectares (gha), capturing the biologically productive land and water required to meet consumption and waste assimilation needs. The key explanatory variable, waste-to-energy (WtE), has been obtained from the APEC database and is measured in kilotons of oil equivalent (Ktoe). This represents the amount of energy generated from municipal solid waste combustion. The other independent variables, such as gross domestic product (GDP), are expressed in constant 2015 US dollars; domestic credit to the private sector serves as a proxy for financial development (FD) and foreign direct investment (FDI) inflows are expressed as net inflows in constant 2015 US dollars. These data have been drawn from the World Development Indicators (WDI) database. Figures 6 and 7 show time series plots for each variable in China and the United States, respectively.

Empirical results and discussion

First, we employ the Phillip Perron unit root test for stationarity. As reported in Table 1, the dependent variable is stationary at the first difference in both countries.

Next, we employ the bounds test to identify the existence of long-run cointegration. As reported in Table 2, all models in both China and the United States are cointegrated at the 99% confidence level.

NARDL. Nonlinear analysis begins by selecting the best specified nonlinear autoregressive distributed lag (NARDL) model. To do this, we first estimate Eq. (2) for each country. The optimal lag length is determined using the widely accepted Akaike information criterion (AIC). Following this, we conduct Wald tests for symmetry to identify the best model specifications. The results are summarized in Table 3, which indicates that the long-run asymmetry for Waste-to-Energy (WtE) is present for both China and the United States. However, the short-run asymmetry for WtE is only applicable to the United States. These findings underscore the importance of accounting for non-linearity and asymmetry in modeling the relationship between waste-to-energy and carbon emissions, as failing to do so may result in spurious regression.

For China, the long-term asymmetric impact of WtE on EFP has been confirmed. Both WtE^+ (positive changes) and WtE^- (negative changes) are statistically significant at the 1% level, with coefficients of -0.1557 and -0.1932 , respectively. This indicates that increases in WtE reduce the ecological footprint, while decreases in WtE increase it. Importantly, the magnitude of WtE^- is larger than that of WtE^+ , indicating that the ecological

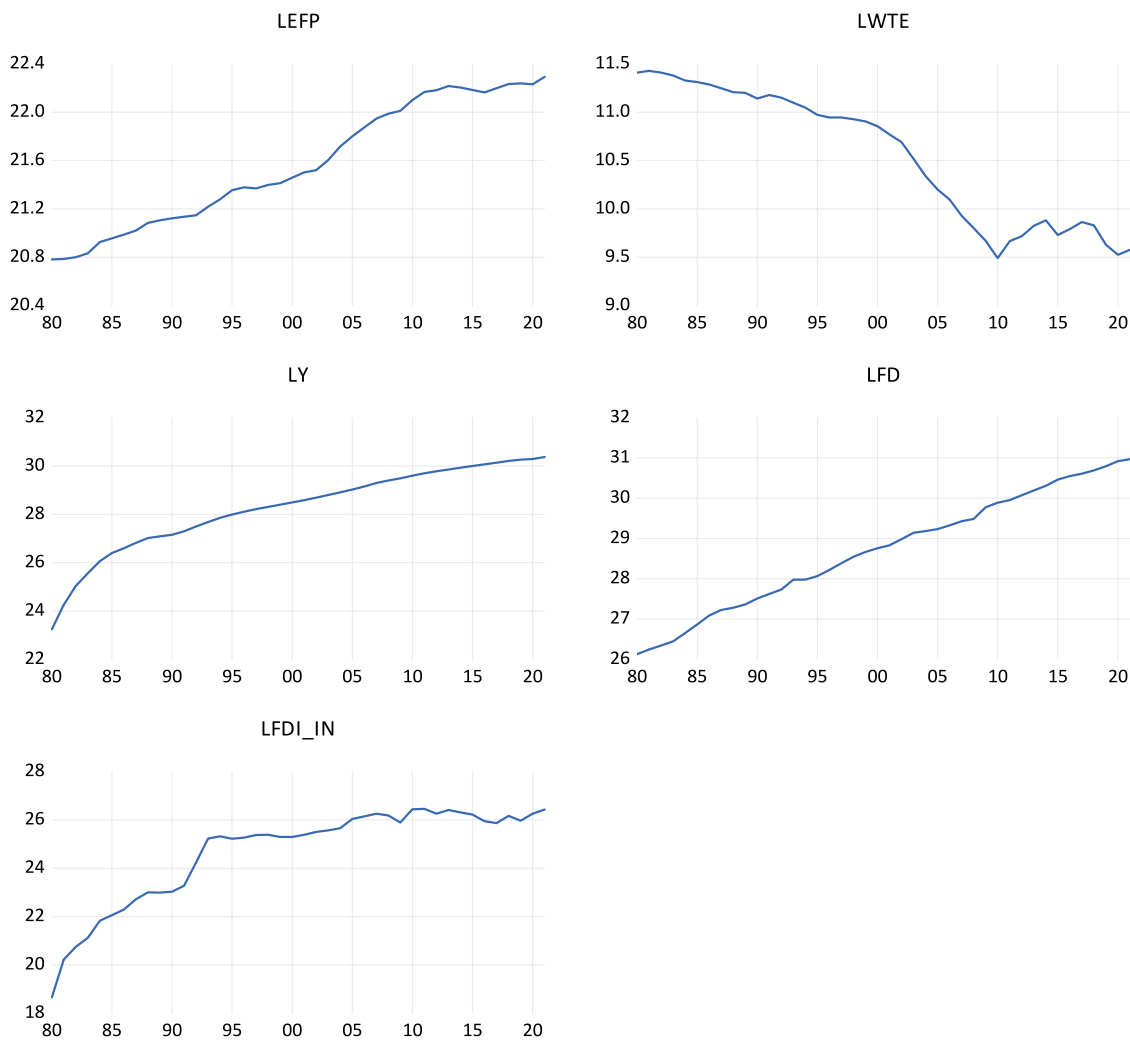


Fig. 6 Time series plots for each variable in China.

footprint in China is more sensitive to the decline of WtE capacity than its expansion.

This outcome underscores the crucial role of WtE in supporting environmental sustainability in China. This is consistent with prior studies, which have highlighted the positive ecological contributions of WtE (Sun et al., 2017; Zhang et al., 2015; Lee et al., 2020). On the benefit side, WtE contributes to reducing greenhouse gas emissions, easing landfill pressure, and enhancing resource recovery, thereby providing clear ecological gains. On the cost side, however, the substantial operational expenses of WtE plants threaten their long-term economic viability and sustainability (Weatherby, 2019; Zhang et al., 2015; Zhao et al., 2016). These contrasting forces suggest that while WtE can deliver meaningful environmental benefits, its success ultimately depends on maintaining stable investment levels and supportive financial mechanisms.

For the United States, the long-term asymmetric impact of WtE on EFP is only partially evident. Here, only WtE^+ is statistically significant, with a coefficient of -0.0126 at the 5% level. Reductions in WtE (WtE^-) do not exert a significant effect. This implies that ecological improvements in the U.S. are primarily driven by the increase in WtE, whereas decreases in WtE capacity do not translate into measurable ecological deterioration. These findings align with earlier works emphasizing the environmental benefits of WtE in the U.S. (Kalair et al., 2021).

However, several structural and institutional factors limit the U.S. experience. While WtE reduces landfill demand and mitigates emissions, high operating costs continue to constrain investment incentives (US Department of Energy, 2019). Moreover, unlike China, the United States allows the export of municipal solid waste, shifting ecological burdens to importing countries, predominantly Malaysia, Vietnam, Indonesia, and Thailand (Bourtsalas et al., 2023). This practice reduces the domestic ecological footprint, but externalizes environmental risks abroad, which may explain the weaker WtE–EFP link in the U.S. as compared to China.

Analyses of both China and the United States demonstrate that GDP and GDP^2 are significant, with positive and negative signs, respectively, confirming the presence of the environmental Kuznets curve (EKC) hypothesis in both countries. Similarly, the variables of financial development (FID) and foreign direct investment (FDI) are significant with positive signs in both countries. In the short run, the asymmetric impact of WtE on EFP is only partially observable in the United States, where only WtE^+ shows a significant negative effect on EFP. On the other hand, in China, none of the exogenous variables are significant in the short run.

Diagnostic tests confirm that both models are well-fitted, and stability is corroborated by CUSUM and CUSUM of squares tests, as reported in Figs. 8–11, indicating that the models are stable.

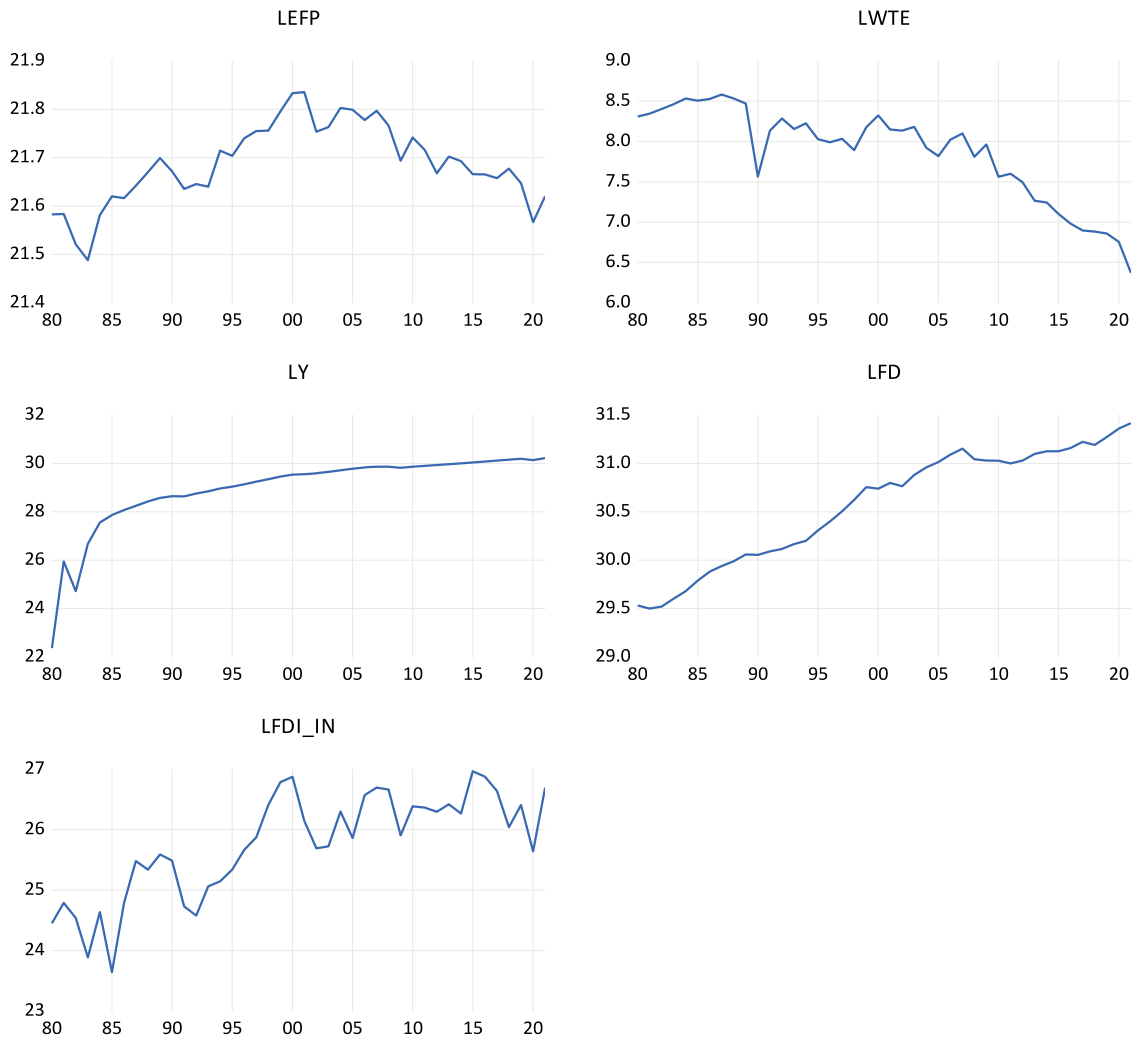


Fig. 7 Time series plots for each variable in the United States.

Table 1 Phillips-Perron unit root test.				
China	Level		First difference	
	Constant	Trend	Constant	Trend
EFP	-0.6256	-1.5579	-3.8850***	-3.9159***
WTE	-0.2999	-1.8973	-4.2262***	-4.1340***
GDP	-1.9168	0.5447	-3.4521***	-3.9012***
FD	-3.6894**	-1.5717	-5.6614***	-7.7560***
FDI	-5.5449***	-3.6618	-5.7533***	-7.1071***
United States	Level		First difference	
	Constant	Trend	Constant	Trend
EFP	-1.7372	-1.0833	-6.3643***	-7.6750***
WTE	0.9964	-2.0054	-8.4186***	-10.4341***
GDP	-2.1849	-0.8656	-5.1871***	-5.4162***
FD	-1.2269	-1.2724	-4.9998***	-5.1286***
FDI	-2.0201	-3.5018	-8.8988***	-9.5696***

*** and ** represent significance at the 1% and 5% significance levels, respectively.

MT-NARDL. We advance our analysis by applying the multi-threshold nonlinear autoregressive distributed lag (MT-NARDL) method to assess the asymmetrical thresholds of waste-to-energy (WtE) impact. Table 4 presents the MT-NARDL estimation models, with threshold values specified at the 25th, 50th, and 75th

percentiles. The coefficients WtE^a , WtE^b , WtE^c , and WtE^d each capture the effects of WtE at values below the 25th percentile, between the 25th and 50th percentiles, between the 50th and 75th percentiles, and above the 75th percentile, respectively. The Wald test confirms the presence of threshold effects in the model for both China and the United States.

The MT-NARDL results provide further evidence of non-linearity, showing a consistent pattern across both China and the United States. In both cases, WtE variables (WtE^a , WtE^b , WtE^c , and WtE^d) are both significant and negative, with coefficients increasing in magnitude at higher thresholds. This confirms that the ecological benefits of WtE are scale-dependent. Modest expansions have limited effects, while larger increases in WtE capacity yield disproportionately stronger reductions in ecological footprint.

For China, all four threshold coefficients ($WtE^a = -0.0053$, $WtE^b = -0.0326$, $WtE^c = -0.2520$, $WtE^d = -0.3860$) are statistically significant at the 5% level. These results indicate that scaling up WtE capacity significantly reduces ecological footprint, with the effect intensifying at higher production levels. This validates the policy rationale for sustained WtE investment. Indeed, China has actively pursued WtE expansion since the early 2000s, making it central to its renewable energy and waste management strategies (Zhang et al., 2015). For example, the Shenzhen East WtE plant, the world's largest incineration facility, processes 2.7 million tons of waste

Table 2 Bounds test.

	Lag length	ARDL bounds test
<i>China</i>		
$EFP = f(WtE^+, WtE^-, GDP, GDP^2, FID, FDI)$	2, 3, 0, 3, 3, 1, 3	11.7485***
$EFP = f(WtE^a, WtE^b, WtE^c, WtE^d, GDP, GDP^2, FID, FDI)$	3, 2, 2, 2, 2, 2, 2, 2	6.3901***
<i>United States</i>		
$EFP = f(WtE^+, WtE^-, GDP, GDP^2, FID, FDI)$	4, 4, 4, 4, 4, 4, 3	7.9201***
$EFP = f(WtE^a, WtE^b, WtE^c, WtE^d, GDP, GDP^2, FID, FDI)$	2, 0, 3, 3, 2, 3, 3, 3	12.1811***

*** represents significance at the 1% significance level.

Table 3 Wald tests for short- and long-run symmetry.

Model	China	United States
WtE_{NARDL_LR}	31.3516***	27.3353***
WtE_{NARDL_SR}	1.4065	5.2055**

*** and ** represent significance at the 1% and 5% significance levels, respectively.

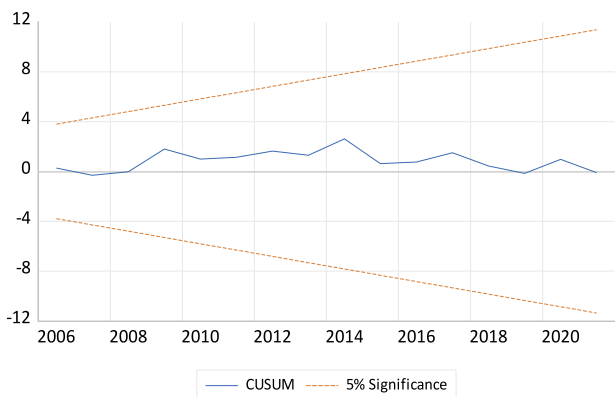


Fig. 8 NARDL CUSUM (China).

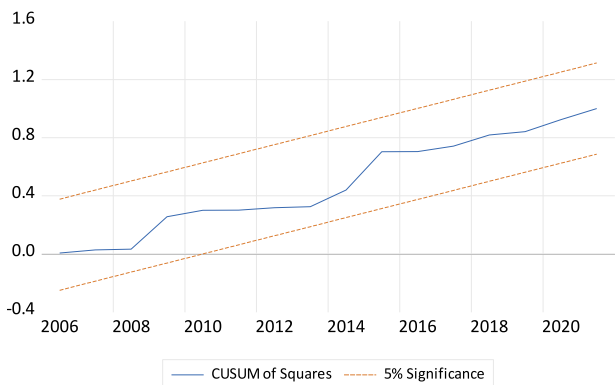


Fig. 9 NARDL CUSUM square (China).

annually and generates 1.5 billion kilowatt-hours of electricity per year (Mordor Intelligence, 2022). In 2019 alone, China invested RMB 35 billion in WtE projects, with 80% of these involving incineration (Cui et al., 2020). By 2017, China’s installed capacity reached 7.3 GW across 339 plants, with projections of 10 GW and 600 plants by 2020 (Weatherby, 2019). These large-scale commitments are consistent with the strong threshold effects captured in the MT-NARDL model.

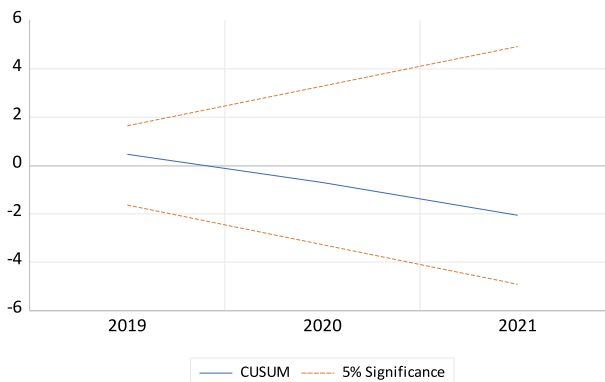


Fig. 10 NARDL CUSUM (United States).

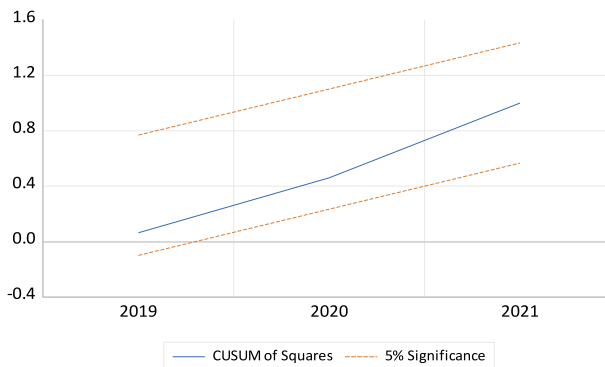


Fig. 11 NARDL CUSUM square (United States).

For the United States, WtE^a , WtE^b , WtE^c , and WtE^d are also statistically significant at the 1% level, with coefficients of -0.0061 , -0.0043 , -0.0348 , and -0.1236 , respectively. These results similarly confirm that expansions in WtE reduce ecological footprint, with stronger effects at higher thresholds. Notably, the short-run coefficients for WtE also follow a consistent negative pattern, suggesting that WtE changes in the U.S. exert immediate as well as long-term effects on ecological outcomes. Although U.S. investment has been less aggressive than China’s, recent developments have demonstrated renewed interest. The U.S. Department of Energy, for instance, allocated USD 3 million to enhance WtE processes and infrastructure (Office of Energy Efficiency and Renewable Energy, 2023). The sector is currently valued at USD 10 billion (WEKA Industrie Medien, 2023) and is expected to grow, driven by concerns over landfill scarcity, greenhouse gas mitigation, and energy security.

A key comparative insight is that WtE has a greater ecological impact in China than in the United States, as consistently demonstrated in both NARDL and MT-NARDL estimations (Tables 3 and 5). This reflects structural differences, as in China,

Table 4 MT-NARDL estimation models.

<i>m</i>	China	United States
Model	3, 2, 2, 2, 2, 2, 2, 2, 2	2, 0, 3, 3, 2, 3, 3, 3, 3
<i>Long run</i>		
WtE ^a	-0.0053**	-0.0061***
WtE ^b	-0.0326**	-0.0043***
WtE ^c	-0.2520**	-0.0348***
WtE ^d	-0.3862**	-0.1236***
GDP	1.0616**	0.6817**
GDP ²	-1.5925**	-1.1315***
FID	0.3437**	0.3347***
FDI	0.1760**	0.0404***
<i>Short run</i>		
ECT	-0.7027**	-0.9625***
WTE ^a	-0.0033	-0.0013***
WTE ^b	-0.0015	-0.0052**
WTE ^c	-0.0050	-0.0053***
WTE ^d	-0.0315	-0.0258***
GDP	0.6084	0.1497
GDP ²	-0.5749	-1.5063
FID	0.1559	0.1503
FDI	0.0936	0.0291
<i>Wald test</i>		
WTE ^a = WTE ^b = WTE ^c = WTE ^d	4.6456***	5.1667***
<i>Diagnostic test</i>		
Jarque-Bera	0.2649	0.2004
Breusch-Godfrey serial correlation LM test	2.7315	2.7684
ARCH	0.1482	2.4651
Ramsey test	0.2027	0.2398

*** and ** represent significance at the 1% and 5% significance levels, respectively.

Table 5 NARDL estimation models.

	China NARDL with WTELR asymmetry	United States NARDL with WTELR and WTESR asymmetry
Model	2, 3, 0, 3, 3, 1, 3	4, 4, 4, 4, 4, 4, 3
<i>Long run</i>		
WTE ⁺	-0.1557***	-0.0126**
WTE ⁻	-0.1932***	0.0706
GDP	7.8922***	1.7219***
GDP ²	-3.8302***	-1.4137***
FID	0.0655**	0.0131**
FDI	0.0979***	0.2973**
<i>Short run</i>		
WTE	-0.0945	-
WTE ⁺	-	-0.1799**
WTE ⁻	-	0.0027
GDP	0.1313	0.3109
GDP ²	0.0016	-0.3745
FID	-0.0322	-0.0886
FDI	-0.0095	0.0159
<i>Diagnostic test</i>		
Jarque-Bera	0.3436	1.2695
Breusch-Godfrey Serial Correlation LM test	2.647	0.6947
ARCH	0.4521	0.1638
Ramsey test	1.8691	0.4866

*** and ** represent significance at the 1% and 5% significance levels, respectively.

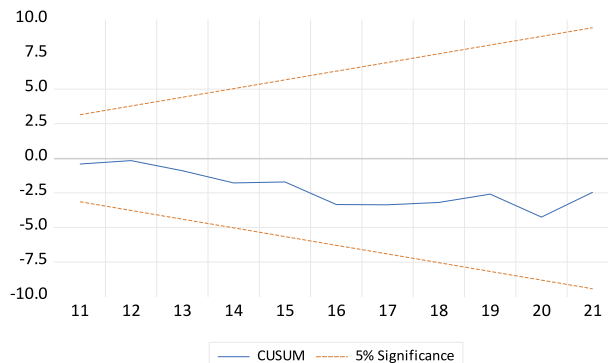


Fig. 12 MT-NARDL CUSUM (China).

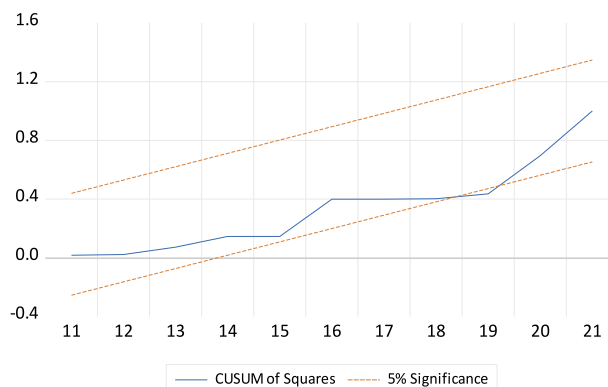


Fig. 13 MT-NARDL CUSUM square (China).

WtE contributes around seven times more to total electricity supply than in the U.S., whereas WtE accounts for <1% (U.S. Energy Information Administration, 2023). Consequently, ecological footprint changes in China are more sensitive to WtE variations.

For the control variables, GDP and GDP2 show significant results with positive and negative signs, respectively, in both countries, confirming the existence of the environmental Kuznets curve (EKC) hypothesis. FDI also shows significant positive effects in both countries. In the short run, an asymmetrical impact of WtE on EFP has been observed only in the United States, where WtE⁺ is negatively significant, indicating an immediate effect of increased waste-to-energy on reducing the ecological footprint.

Diagnostic tests confirm the good fit of both models, and stability is corroborated by CUSUM and CUSUM of squares tests as reported in Figs. 12–15, affirming that each model is stable and reliable.

Robustness checks. The robustness check results are presented in Tables 6 and 7, and they are consistent with the primary findings, further strengthening the robustness of our conclusions. When urban population is included as an additional control variable, most models show that urbanization significantly contributes to the ecological footprint in both China and the United States. This result aligns with expectations, as higher urbanization intensifies energy consumption, waste generation, and infrastructure expansion, which together increase environmental pressure (Franco et al., 2017b; Wang et al., 2016). Conversely, well-managed urban growth, accompanied by efficient waste management systems and renewable energy integration, can help mitigate these impacts, underscoring the dual role of urbanization as both a driver and

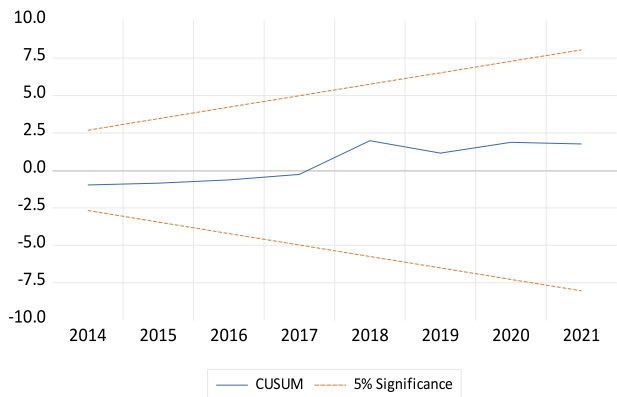


Fig. 14 MT-NARDL CUSUM (United States).

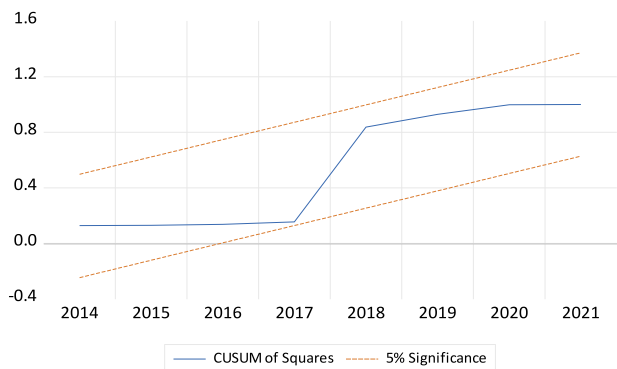


Fig. 15 MT-NARDL CUSUM square (United States).

Table 6 Robustness checks for NARDL estimation models.

	China NARDL with WTELR asymmetry	United States NARDL with WTELR and WTESR asymmetry
Model	1, 1, 1, 0, 0, 0, 1, 0	1, 0, 3, 0, 0, 0, 3, 2
<i>Long run</i>		
WTE ⁺	-0.1702***	0.1203***
WTE ⁻	-0.9796**	0.4475
GDP	1.2922**	2.1440***
GDP ²	-8.3252**	-2.2662***
FID	1.5909**	0.0068**
FDI	0.2609**	0.6433**
UP	3.5779**	2.2629**
<i>Short run</i>		
WTE	-0.0711	-
WTE ⁺	-	-0.0563***
WTE ⁻	-	-0.0039
GDP	-0.6131	-0.7976
GDP ²	0.5998	1.1031
FID	-0.1820	0.0033
FDI	0.0227	0.1849
UP	2.4204	0.7473
<i>Diagnostic test</i>		
Jarque-Bera	1.1587	1.1704
Breusch-Godfrey Serial Correlation LM test	1.6810	0.9539
ARCH	0.8238	0.7691
Ramsey test	2.0859	0.4811

*** and ** represent significance at the 1% and 5% significance levels, respectively.

Table 7 Robustness checks for MT-NARDL estimation models.

	China	United States
Model	1, 0, 0, 0, 1, 0, 1, 0, 0, 0	1, 1, 0, 0, 0, 1, 0, 1, 1, 0
<i>Long run</i>		
WtE ^a	-0.0001**	-0.0037***
WtE ^b	-0.0063**	-0.0039**
WtE ^c	-0.0131**	-0.0932**
WtE ^d	-0.4321**	-0.8690**
GDP	0.3583***	1.0677***
GDP ²	-0.3617***	-1.3322***
FID	0.2557***	0.2357***
FDI	0.1643**	0.0435***
UP	1.2517**	0.8173
<i>Short run</i>		
ECT	-0.4349***	-0.8306***
WTE ^a	-0.0002***	-0.0017***
WTE ^b	-0.0007***	-0.0041***
WTE ^c	-0.0026**	-0.0221**
WTE ^d	-0.0585***	-0.0754***
GDP	0.7307***	-1.1656
GDP ²	-0.8185***	1.5701
FID	-0.1517	0.0468
FDI	0.0816	0.0003
UP	2.0343***	2.3096
<i>Wald test</i>		
WTE ^a = WTE ^b = WTE ^c = WTE ^d	2.5438**	5.7500***
<i>Diagnostic test</i>		
Jarque-Bera	0.4358	0.5008
Breusch-Godfrey serial correlation	1.8052	1.4749
LM test		
ARCH	1.2630	0.1135
Ramsey test	0.0779	1.5577

*** and ** represent significance at the 1% and 5% significance levels, respectively.

potential mitigator of ecological stress (Franco et al., 2017a; Li et al., 2016).

Conclusion and operational applicability

This study presents a comprehensive nonlinear analysis to explore the potential impact of waste-to-energy (WtE) on the ecological footprint in China and the United States. Using both NARDL and MT-NARDL models, we analyzed a time series sample dataset from 1980 to 2021. Our findings indicate that an increase in WtE tends to reduce the ecological footprint. Conversely, a decrease in WtE leads to an increase in the ecological footprint in China, but does not affect any changes in the ecological footprint in the United States. Additionally, the more municipal solid waste is utilized for energy generation, the more the ecological footprint is reduced in both countries. Our econometric findings strongly suggest that WtE, as an alternative method for municipal solid waste combustion, has the potential to improve environmental quality by reducing the ecological footprint.

Our research highlights not only economic considerations but also the critical aspect of environmental sustainability. We recommend a comprehensive financial aid package with three stages of execution to support the WtE industry on the supply side. In the initial stage, it is essential for governments to provide subsidies to enhance the operational capabilities of WtE plants. These subsidies are strategically designed to cover both operational costs and establish a significant cost advantage, serving as a strong incentive for these facilities to not only survive but also to thrive as an industry.

The cost of utilizing green technology in WtE plants is significantly high. It is crucial to ensure that financial support is directed specifically towards WtE plants that comply with strict environmental criteria. The practical execution of this plan promotes the adoption of eco-friendly technologies by allocating subsidies specifically for WtE plants committed to implementing green practices, ensuring that their operations align with sustainability principles.

Transforming municipal solid waste into useful energy is a transformative method that is a cost-effective option, which acts as a strategic step towards establishing a circular economic framework for a sustainable energy future. Emphasizing strict compliance with environmental regulations ensures that WtE becomes the most favorable and cost-effective option for incinerating solid municipal waste, establishing WtE plants as leaders in the industry. By adopting green technology, these plants can gain a competitive edge and position themselves as crucial contributors to a circular economic framework promoting energy sustainability.

Recognizing the financial strains of a long-term subsidy program, we transition to the second stage, which emphasizes a practical approach. Introducing soft loans for technological upgrades becomes a key strategy, providing WtE plants with financial support for substantial green technological improvements. This targeted approach advocates for investments specifically in high-tech solutions that prioritize environmental friendliness, enhancing the efficiency of WtE plants and significantly reducing their ecological footprint. This aligns with broader sustainable development goals, making the operational landscape of these plants more environmentally friendly and efficient.

In the third stage, the government should offer tax relief to WtE plants. This strategic move will encourage these plants to maintain their industry presence, fostering long-term environmental impact. Unlike subsidies and soft loans, tax relief provides ongoing support and aligns with fiscal responsibility, ensuring that WtE plants receive financial benefits proportional to their commitment to minimizing environmental impact.

Furthermore, to strengthen WtE initiatives on the demand side, we recommend introducing a Feed-In Tariff (FIT) scheme, which ensures that renewable energy producers receive a premium price for their electricity through long-term contracts. This will create stable and attractive investment prospects when extended to both individuals and businesses, facilitating a faster transition to renewable energy.

Our findings point to the need for differentiated policies tailored to specific national contexts. For China, the results confirm that both increases and decreases in WtE significantly affect the ecological footprint, with a greater sensitivity to declines. This asymmetry indicates that even small contractions in WtE can cause disproportionately larger ecological harm compared to the benefits of expansion. Policymakers should therefore prioritize stability and continuity of WtE investment to avoid disruptions, alongside financial instruments such as subsidies, concessional loans, and public-private partnerships to sustain growth in the sector.

Furthermore, since rapid expansion is already underway, strict emission-control standards and advanced abatement technologies must be mandated to ensure that ecological gains are not undermined by secondary pollution risks. A clear example is the Shenzhen East WtE plant. While this demonstrates the ecological and energy benefits of large-scale, technologically advanced plants, it also highlights challenges, such as high operating costs, public concerns over emissions, and the need for strong regulatory oversight. These challenges reinforce our recommendation that China combine stable financial support with stringent

environmental regulation to ensure that WtE contributes sustainably to its circular economy agenda.

For the United States, the evidence shows that only increases in WtE are significant, while declines have no measurable ecological effect. This implies that U.S. policy needs to create stronger incentives for new WtE deployment, as ecological improvements are only realized when capacity expands. A regionalized approach is particularly relevant, as states with landfill scarcity would benefit most from new WtE investment, while others may integrate WtE with recycling strategies to balance cost and efficiency. Notable facilities such as Wheelabrator in Florida and Covanta Essex in New Jersey illustrate how regionally targeted plants can relieve landfill pressures and supply renewable electricity. However, these projects have faced challenges, such as local opposition due to air quality concerns, high capital costs, and competition with cheaper landfilling options. These constraints align with our recommendation that the U.S. rely on tax incentives, Feed-in Tariff (FIT) schemes, and renewable portfolio standards to improve financial attractiveness, while also implementing stricter environmental safeguards and export regulations to ensure ecological gains are realized domestically rather than shifted abroad.

This study is not without limitations. A key constraint lies in the reliance on time-series data, which restricts the analysis to China and the United States as the only countries with more than 30 years of consistent Waste-to-Energy (WtE) data available. While this long horizon enables robust nonlinear analysis, it also limits the generalizability of the findings to other contexts. Looking ahead, future studies could employ panel data approaches once more countries accumulate sufficiently long records of WtE activity, a prospect that appears increasingly feasible in the next five years as WtE gains global prominence under the circular economy agenda supporting sustainable futures. Additionally, future research could incorporate spatial econometric methods to capture potential spillover effects across countries, as well as the negative externalities associated with cross-border waste trade and transboundary environmental impacts.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

DHH wrote the conceptualization, methodology, data curation, visualization, investigation, writing—original draft, writing—reviewing and editing. HHL wrote the conceptualization, methodology, supervision, validation, writing—original draft, writing—reviewing and editing. AA wrote the conceptualization, writing—original draft, writing—reviewing and editing.

Competing interests

The authors declare no competing interests.

Ethical approval

This study does not involve human participants or their data. Therefore, ethics approval was not required for this research. The analysis uses secondary data from existing sources, and the study complies with all relevant ethical guidelines and regulations.

Informed consent

This study does not involve human participants or their data. As a result, informed consent was not obtained or required. The research relies on secondary data from existing sources and does not engage with any personal or identifiable information, ensuring compliance with all relevant ethical guidelines and regulations.

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