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NONLINEAR DRIVING MECHANISMS OF INDUSTRIAL SOLID WASTE GENERATION IN CHINA: A GENERALIZED ADDITIVE MODEL APPROACH

This study applied China's provincial panel data from 2007 to 2023 and the Generalized Additive Model (GAM) to examine the nonlinear driving mechanisms of general industrial solid waste generation (GISWG). The results showed that China's GISWG reached a negative growth inflection point in 2016, and the influencing factors exhibit significant nonlinear characteristics. Specifically, per capita GDP (PCGDP) presents an inverted U-shaped trajectory, with a critical turning point identified at approximately CNY 135,000 per person (approximately USD 19,158 per person), validating the existence of the Environmental Kuznets Curve (EKC). Moreover, industrial added value (IAV) shows oscillating fluctuations, while main business revenue of industrial enterprises (MBRIE) demonstrates diminishing marginal effects beyond the threshold of CNY 11 trillion (approximately USD 1.56 trillion). Technological innovation exhibits a U-shaped pattern, signaling a transition from substantive mitigation to a potential rebound effect once domestic patent applications exceed 400,000 items. Spatially, the impact of economic factors is primarily concentrated in developed and heavy-industrial regions, while governance factors vary significantly across regions. This study provides empirical evidence for identifying governance thresholds and offers actionable strategies for Zero-waste City construction.

1. INTRODUCTION

Industrial solid waste is one of the major sources of environmental pollution, and its continuously increasing generation poses a significant threat to the ecological environment and human health. As the world's largest industrial producer, China has seen a persistent rise in industrial solid waste generation, reaching its highest level during the study period in 2023. Research indicates that economic growth is closely linked to solid waste

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generation, with the advancement of industrialization directly driving an increase in solid waste emissions [1]. Improperly managed industrial solid waste not only consumes land resources but may also cause secondary pollution through water bodies, soil, and other media. From a policy evolution perspective, the prominence of industrial solid waste issues within the environmental governance framework has grown increasingly significant [2]. In recent years, the implementation of the Zero-waste City pilot policy signifies China's entry into a new phase of systematic management for industrial solid waste. Despite these efforts, the generation of industrial solid waste remains unchecked, with the complexity of its underlying drivers being a key factor in the governance challenges.

However, the specific driving mechanisms remain unclear due to the non-linear interactions among these factors. The generation of industrial solid waste is closely linked to factors such as economic development, industrial structure, and technological innovation, yet this relationship is not a simple linear correlation. Existing research has examined the influencing factors of solid waste generation from various perspectives, but most studies focus on single-dimensional or linear relationship analyses, with insufficient attention paid to the complex interactions and nonlinear characteristics among these factors. Given the complex socioeconomic factors and China's uneven regional development, identifying the mechanisms influencing industrial solid waste generation, determining critical governance thresholds, and formulating tailored management policies represent key challenges in building Zero-waste City – the starting point of this research.

To address these gaps and provide robust policy implications, this study proposes a novel analytical framework. Compared with existing research, the innovation of this paper lies primarily in three aspects. First, innovation in research content. Existing studies are often confined to single-dimensional indicators, lacking comprehensive consideration of multiple driving factors. This study comprehensively examines the impact of multidimensional factors – including economic scale, industrial structure, technological innovation, consumption patterns, and environmental governance-on GISWG. It further incorporates novel consumption-driven indicators such as express delivery volume (EDV) and private vehicle ownership. Second, methodological innovation. Existing studies predominantly employ traditional linear models, which struggle to capture complex nonlinear relationships between variables. This paper employs a Generalized Additive Model (GAM) to explore the nonlinear effects of various drivers on solid waste generation. GAM automatically learn nonlinear relationships within data and identify critical threshold values. Third, the validity of research conclusions. By using GAM to investigate the dynamic trends of various factors' effects on solid waste generation, this study provides precise guidance for policy formulation, aids in identifying differentiated regional governance pathways, and optimizes resource allocation.

Industrial solid waste. Industrial solid waste primarily refers to solid waste generated during industrial production activities, with its volume closely linked to the pace of industrialization. From an industrial park perspective, Yu et al. [3] analyzed the current status of multi-source solid waste disposal in typical Chinese industrial parks, highlighting that

integrated disposal and recycling represent crucial pathways for achieving resource conservation and environmental protection. Addressing express packaging waste, Zhou et al. [4] employed life cycle assessment to compare the environmental impacts of traditional versus recyclable packaging. They found that recyclable express boxes and bags reduced overall environmental impacts by 63% and over 26%, respectively, compared to conventional packaging. Regarding management efficiency assessment, Guan et al. [5] conducted a dynamic evaluation of industrial solid waste management efficiency across Chinese provinces, revealing generally low efficiency in the resource reuse stage and higher treatment efficiency in western regions compared to eastern regions.

With the advancement of the Zero-waste City pilot policy, evaluating its effectiveness has become a research hotspot. Li et al. [6] employed a difference-in-differences approach to assess the policy's benefits in hazardous waste lifecycle management, finding that its impact primarily manifests in source reduction. Qian et al. [7] further analyzed the policy using a dual machine learning model, confirming that the Zero-waste City initiative drives corporate green transformation through multiple channels: promoting green technological innovation, strengthening government environmental oversight, and enhancing investors' environmental awareness.

Factors influencing industrial solid waste generation. Factors influencing industrial solid waste generation can be systematically analyzed through the lenses of economic development, technological innovation, consumption patterns, and environmental regulation. At the level of economic development, the environmental Kuznets curve hypothesis is widely used to explain the relationship between economic growth and environmental pollution. Studies based on provincial-level panel data in China reveal that carbon emissions, wastewater discharge, and industrial solid waste emissions all exhibit an inverted U-shaped pattern [8]. Spatial dynamic panel model analysis indicates that an inverted U-shaped relationship also exists between air pollution and economic growth [9]. Studies using multinational samples reveal an N-shaped relationship between GDP and carbon dioxide emissions [10]. In the field of industrial solid waste research, input-output table analysis identifies key supply chains contributing to solid waste generation, confirming that economic expansion is the dominant driver of solid waste growth [11]. Predictive studies employing principal component analysis nonlinear autoregressive back propagation (PCA-NARBP) neural networks further validate that economic indicators such as industrial value-added and corporate profits significantly drive solid waste growth [12].

Technological innovation is regarded as the key pathway to resolving the paradox between economic growth and environmental pressures. From a micro-enterprise perspective, green patents can reduce the intensity of industrial exhaust and wastewater emissions, though their emission reduction effects are weaker than those of end-of-pipe treatment facilities [13]. Environmental information disclosure significantly improves corporate environmental and financial performance by promoting green innovation [14]. Further analysis reveals that environmental performance enhances corporate profitability through

multiple channels: fostering green technological innovation, easing financing constraints, and increasing operating revenues [15].

The evolution of consumption patterns is emerging as a new driver of industrial solid waste generation. The expansion of the express delivery industry has led to a rapid increase in packaging material waste and transportation-related carbon emissions [16]. The significant growth in EDV has substantially boosted carbon emissions, exhibiting pronounced regional heterogeneity [17]. Specifically, the surge in EDV acts as a downstream demand trigger that propagates through the supply chain, significantly stimulating the upstream production of packaging materials such as corrugated paper and plastics. This increased manufacturing activity in the packaging sector in turn drives the generation of general industrial solid waste during these industrial processes. The rise in private car ownership (PCO) stimulates capacity expansion in upstream high-waste industries like steel and rubber, acting as a demand-side driver for industrial solid waste generation [18]. Vehicle purchase restriction policies improve air quality by reducing private car usage, though policy effects exhibit lagging impacts [19].

Environmental regulations, as a key tool for government intervention in environmental governance, have drawn widespread attention for their effectiveness. Different types of environmental regulations exert nonlinear effects on industrial structure upgrading; command-and-control regulations exhibit an inverted U-shaped pattern, while market-based incentive regulations display a U-shaped pattern [20]. The impact of different types of environmental regulations on green industrial development also exhibits nonlinear characteristics, with both types sharing a single threshold for technological progress and fiscal decentralization [21]. At the level of opening up, China's outward foreign direct investment (FDI) influences domestic environmental quality through industrial transfer effects, and an expansion in the scale of outward FDI helps reduce domestic pollution emissions [22].

While existing literature has laid a foundational understanding of the drivers behind industrial solid waste, significant limitations remain. First, the majority of studies rely on linear regression models or logarithmic mean division index (LMDI) decomposition methods, which assume a monotonic linear relationship between socioeconomic variables and waste generation. This approach often overlooks the nonlinear characteristics and phased threshold effects that are prevalent in complex systems. Second, existing indicator systems predominantly focus on macroeconomic variables, giving insufficient consideration to emerging consumption-side drivers such as EDV and private vehicle ownership, thus failing to fully capture the environmental pressures exerted by new economic formats. Consequently, traditional parametric models struggle to accurately depict the complex interactions among multidimensional factors. To address these gaps, this study employs GAM, a highly interpretable non-parametric approach. By avoiding pre-specified functional forms, the GAM allows for a data-driven identification of nonlinear response curves and critical governance thresholds for each driver, thereby offering a more nuanced perspective on the complex mechanisms driving industrial solid waste generation.

The conceptual framework diagram of this article is shown in Fig. 1, where mgcv refers to mixed GAM computation vehicles with automatic smoothness estimation, an R package used for fitting generalized additive models.

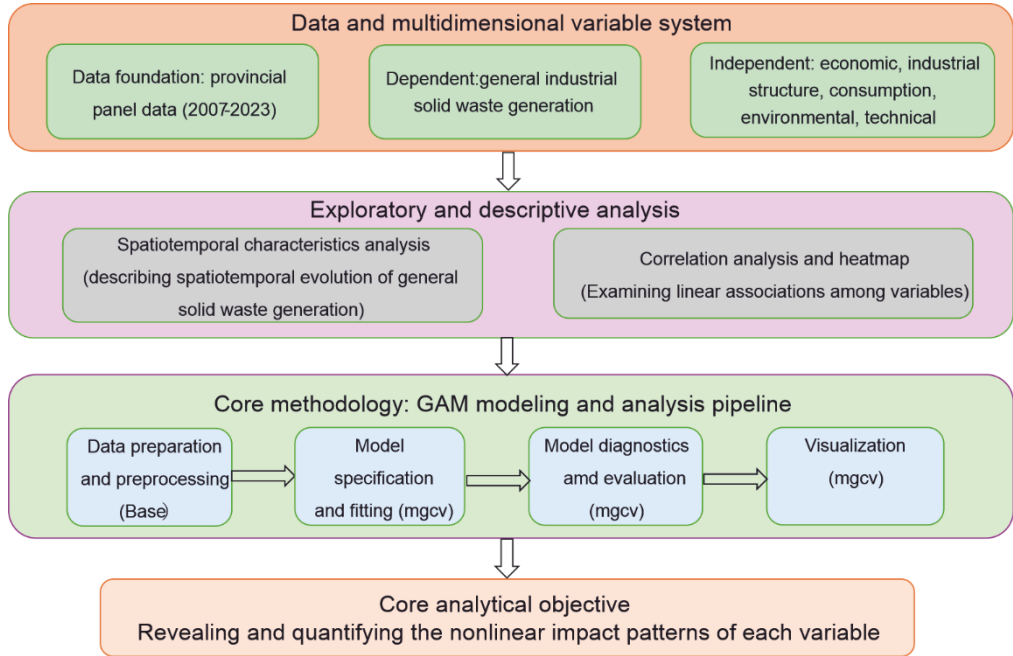


Fig. 1. Conceptual framework diagram

2. EXPERIMENTAL

Research methodologies. In the field of environmental research, GAM has been successfully applied to analyze drivers of air pollution. Li et al. [23] employed GAM combined with principal component analysis to estimate PM_{2.5} concentrations, finding this method effective for air pollution mapping by capturing complex relationships between meteorological factors and pollutant concentrations. Ma et al. [24] employed GAM to analyze the drivers of PM_{2.5} in the Tianshan North Slope urban cluster, confirming that the interaction between meteorological factors and pollutant emissions exerts a stronger influence on PM_{2.5} than either factor alone. These studies demonstrate GAM's unique advantage in revealing the nonlinear characteristics of environmental influencing factors. Therefore, this research adopts the aforementioned approach, utilizing GAM to identify the key drivers of industrial solid waste generation and their nonlinear impact patterns.

GAM represents a nonparametric extension of generalized linear models (GLM) proposed by Hastie and Tibshirani [25]. Their core concept involves replacing the predictor variables in linear models with smoothing functions. This enables the model to flexibly capture complex nonlinear relationships between independent and dependent variables without requiring a predefined functional form [26]. The expression is:

$$g(E(Y|X)) = \beta_0 + f_1(X_1) + f_2(X_2) + \dots + f_p(X_p) + \varepsilon \quad (1)$$

where Y denotes the dependent variable, representing the amount of general industrial solid waste generated, $E(Y|X)$ represents the expected value of Y given the independent variable X , g denotes the link function, β_0 is the intercept term; and ε is the random error term.

This paper employed the `mgcv` package in R to fit GAM. The model incorporating spline functions is primarily constructed using the `gam` function. The algorithm utilizes Penalty Iterative Regularized Least Squares (P-IRLS): while keeping the spline coefficients of other independent variables unchanged, it sequentially updates the spline terms of individual independent variables until the entire model converges.

Compared to traditional parametric regression models, the selection of GAM is primarily based on the following significant advantages:

1. Without requiring predefined functional forms for independent and dependent variables, it can automatically learn nonlinear relationships from data, meeting the needs of exploratory analysis;
2. The additive structure allows the marginal contribution of each explanatory variable to be interpreted independently, facilitating the identification of differential impacts of various factors on solid waste generation;
3. By controlling smoothness through the penalty term, overfitting is effectively prevented, thereby enhancing the model's generalization capability.

Definition of variables. The study area corresponded to China's administrative divisions. Data were sourced from the *China Statistical Yearbook*³, covering 30 provinces (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2007 to 2023. The data type is panel data.

To systematically analyze the driving mechanisms of industrial solid waste, this study selected GISWG as the dependent variable. Drawing upon existing research on environmental economic pressures and pollution driving mechanisms, the indicators selected for this study are: general industrial solid waste generation (GISWG), investment in industrial pollution control (IIPC), express delivery volume (EDV), private car ownership (PCO), GDP per capita (PCGDP), municipal waste harmless treatment rate (MWHT), domestic

³*China Statistical Yearbook*, National Bureau of Statistics of China, Beijing: China Statistics Press, 2007–2023.

patent applications accepted (DPAA), industrial added value (IAV), Total profits of industrial enterprises above designated size (TPIE), main business revenue of industrial enterprises above designated size (MBRIE). This study focuses on the overall effect of regional innovation activity rather than exclusively green innovation, as innovation may simultaneously generate efficiency gains and scale expansion effects. Full forms of GISWG and related variables are provided in Table 1.

Table 1

Full forms of GISWG and related variable

Variable	Full form	Unit
GISWG	general industrial solid waste generation	104 tons
IIPC	investment in industrial pollution control	CNY 104
EDV	express delivery volume	104 pieces
PCO	private car ownership	104 vehicles
PCGDP	GDP per capita	CNY per person
MWHT	municipal waste harmless treatment rate	%
DPAA	domestic patent applications accepted	number of
IAV	industrial added value	CNY 10 ⁸
TPIE	total profits of industrial enterprises above designated size	CNY 10 ⁸
MBRIE	main business revenue of industrial enterprises above designated size	CNY 10 ⁸

Table 2 presents descriptive statistics for the provincial-level panel observations. GISWG ranged from 157.9×10^4 tons to $49,357 \times 10^4$ tons across province-year observations, with a mean of $10,560 \times 10^4$ tons. These values represent individual provincial observations rather than national aggregate totals.

Table 2

Descriptive statistics of provincial-level panel variables

Variable	Mean	Min	Q_1	Median	Q_3	Max
GISWG	10,560	157.9	4,485	7,820.5	1,3725	49,357
IIPC	189,997	476	72,705	131,513	238,606	1,416,464
EDV	133,304	144	3,844	19,970	102,388	3,456,729
PCO	499.98	7.89	144.78	345.94	643.15	2,705.7
PCGDP	54,038	7,875	30,750	46,639	67,529	216,722
MWHT	8,866	23	83.5	96.75	100	100
DPAA	96,483	387	13,514	42,648	109,019	993,480
IAV	8,486.1	207.5	3176.3	5,755	10,782.4	47,642.7
TPIE	2,114.6	-528.8	674.1	1,461.7	2,588.6	11,595.2
MBRIE	32,621.1	785.9	10,047	21,385.2	41,052.6	185,496.9

3. RESULTS AND DISCUSSION

3.1. SPATIOTEMPORAL DISTRIBUTION OF GISWG

GISWG data from 2007 to 2023 were collected from the China Statistical Yearbook. Using 2007 as the base year, the year-on-year growth rate of GISWG was calculated. Figure 2 illustrates the temporal evolution of national aggregate GISWG and its growth rate, which was calculated by summing provincial GISWG across the 30 provinces for each year. As shown in Fig. 2, GISWG exhibits an overall upward trend. The temporal evolution of GISWG can be divided into three distinct phases: 2007–2011, 2011–2018, and 2018–2023. During the first phase, GISWG exhibited an upward trajectory. The second phase featured a flatter trend with a slight decline. The third phase mirrored the growth pattern of the first phase, reaching its peak during the observation period in 2023 ($427,001 \times 10^4$ tons). However, the growth rate in this phase was lower compared to the first phase, this coincides with the timeline of the Zero-Waste-City policy implementation.

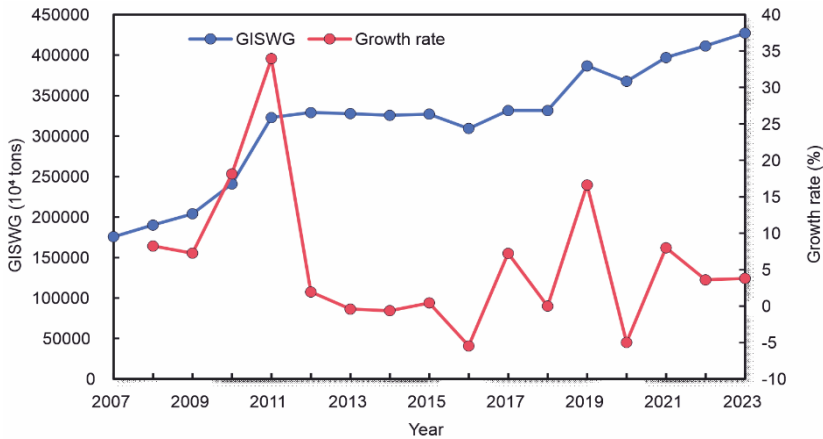


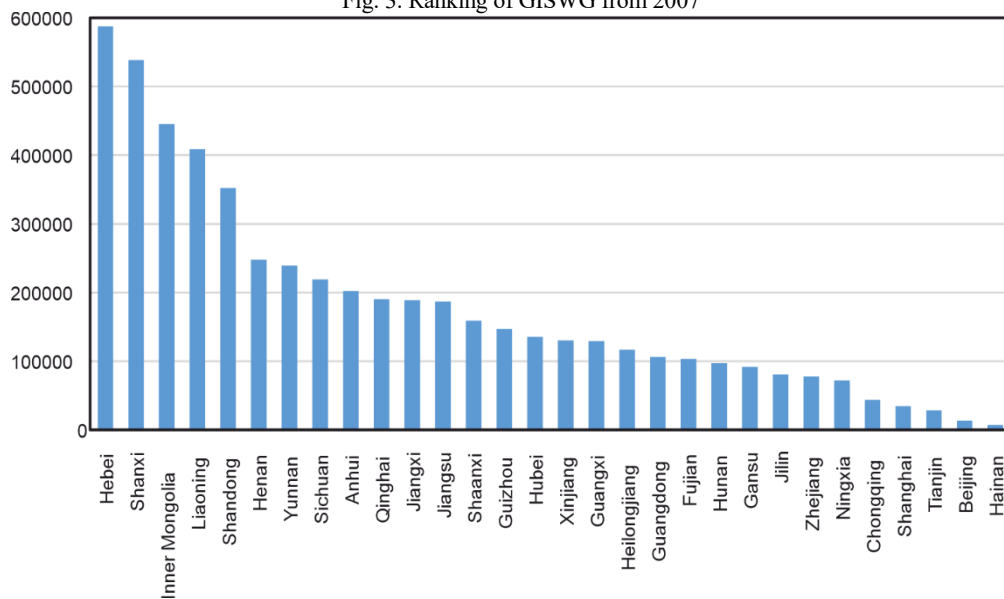
Fig. 2. Temporal evolution of GISWG and its growth rate from 2007 to 2023

The trend in GISWG growth rates indicates fluctuations in its changes. From 2008 (8.25%) to 2023 (3.80%), the growth rate generally showed a downward trend, reaching a negative growth rate in 2016, which was the lowest point during the observation period (−5.46%). This turning point can be attributed to the combined effects of economic restructuring, stricter policy measures, industrial upgrading, the advancement of the circular economy, and tighter import controls.

China's vast territory exhibits spatial heterogeneity in the generation of general industrial solid waste. Figure 3 shows the distribution of industrial solid waste generation across 30 provinces in China from 2007 to 2023, Hebei Province ($587,640.81 \times 10^4$ tons) generated the highest volume of general industrial solid waste in China, followed by Shanxi

Province ($538,700.54 \times 10^4$ tons) and Inner Mongolia ($445,253.73 \times 10^4$ tons). Anhui Province ($202,493.50 \times 10^4$ tons), Qinghai Province ($190,536.90 \times 10^4$ tons), Jiangxi Province ($188,937.88 \times 10^4$ tons), and Jiangsu Province ($186,954.57 \times 10^4$ tons) follow closely behind.

Fig. 3. Ranking of GISWG from 2007



2023 for various provinces in China

to

Most regions in China with high industrial solid waste generation are concentrated in the industrialized eastern and central areas. These regions lead significantly in industrial solid waste production due to their dense industrial layouts and vibrant economic activities. One possible reason is the maturity of industrial systems in these areas, particularly the concentration of heavy industry and manufacturing sectors that generate substantial industrial solid waste during production. Concurrently, their large populations and extensive urban areas lead to concentrated municipal solid waste generation, providing both industrial and demographic support for high solid waste output. In contrast, some western provinces feature industrial structures dominated by agriculture and specialized light industries, with fewer industrial solid waste generation points and lower population densities, resulting in relatively limited solid waste production. Furthermore, the developmental stage of eastern and central regions influences solid waste generation. Provinces in the middle stages of industrialization often exhibit insufficient application of solid waste reduction technologies in production processes. Conversely, some western provinces prioritizing ecological conservation have effectively controlled solid waste generation through industrial upgrading and the implementation of environmental policies.

3.2. EVALUATION OF THE GAM

An initial understanding of the correlation structure between GISWG and the explanatory variables can be gained from the heatmap of correlation coefficients shown in Fig. 4. It is important to emphasize that correlation coefficients reflect only linear relationships and do not indicate causal effects or nonlinear patterns. Therefore, this section serves solely as descriptive reference. Analysis reveals that GISWG exhibits positive correlations with indicators of completed IIPC and industrial economic scale, while showing weak or near-zero correlations with certain development level indicators. This suggests that subsequent research should employ models capable of capturing nonlinear relationships to further identify true marginal effects.

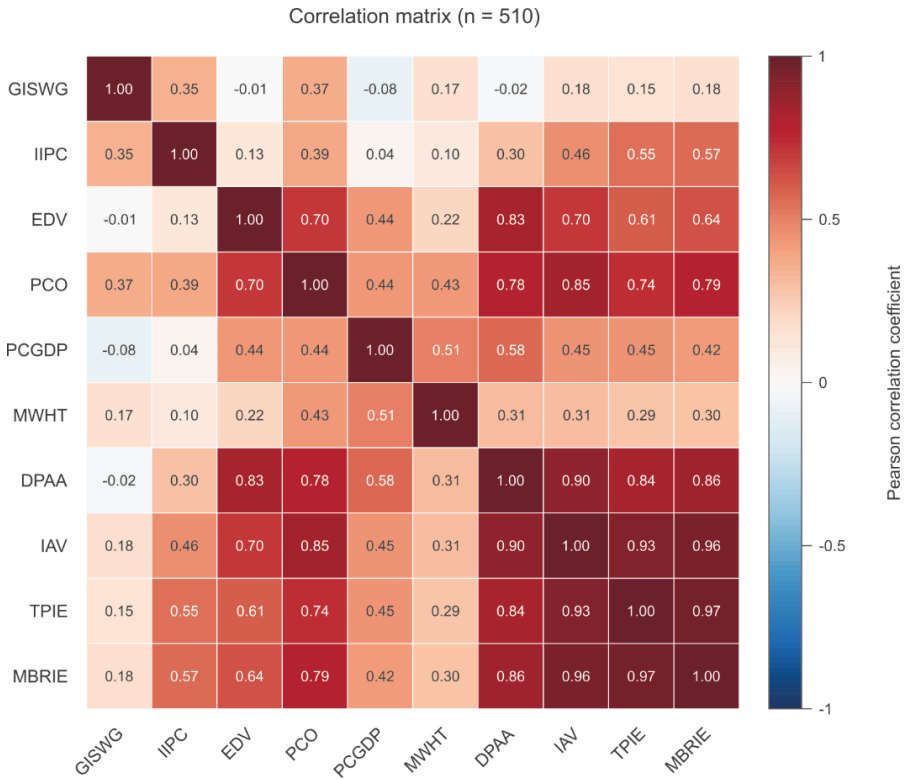


Fig. 4. Heatmap of variable correlation coefficients

However, correlation coefficients can only reflect the degree of linear correlation between variables, failing to reveal causal relationships or potential nonlinear characteristics. Specifically, the Environmental Kuznets Curve (EKC) theory posits that environmental pollution levels may exhibit an inverted U-shaped nonlinear relationship with economic devel-

opment – rising initially before declining. The weak negative correlation observed between PCGDP and GISWG in this analysis may indicate that, within the observed sample range, the relationship between economic development and solid waste generation has entered the declining phase on the right side of the curve described by this theory. This represents only a preliminary observation based on linear correlation. To rigorously investigate the drivers of GISWG and test the validity and specific form of the EKC theory within this research context, the subsequent analysis employs GAM. This model not only accurately identifies the true relationship between economic growth and environmental pressure but also provides a robust theoretical foundation and empirical support for developing differentiated solid waste management strategies tailored to distinct stages of economic development.

Table 3

Results of GAM analysis

Variable	EDF	<i>F</i>	<i>p</i> -value
IIPC	4.911	6.391	1.86×10^{-6}
EDV	8.759	10.935	$< 2 \times 10^{-16}$
PCO	7.257	59.109	$< 2 \times 10^{-16}$
PCGDP	4.335	9.854	$< 2 \times 10^{-16}$
MWHT	1	0.552	0.458026
DPAA	7.913	22.051	$< 2 \times 10^{-16}$
IAV	8.082	15.168	$< 2 \times 10^{-16}$
TPIE	7.826	4.41	0.000409
MBRIE	5.989	9.238	$< 2 \times 10^{-16}$

In the analysis of influencing factors for GISWG (Table 3), except for the *p*-value of municipal waste harmless treatment rate (MWHT) being 0.458 (greater than 0.05) and failing the significance test, the *p*-values of the smoothing terms for all other variables were less than 0.05. This indicates that variables such as industrial pollution control investment (IIPC), EDV, PCO, and other variables significantly influence solid waste generation.

The estimated degrees of freedom (EDF) value serve as crucial indicators for measuring a variable's contribution to a model. If the EDF value of a smoothing term exceeds 1 and passes the significance test, it typically indicates a nonlinear relationship between that variable and the response variable. As shown in Table 3, except for MWHT, the EDF values of the smoothing terms for all other variables are significantly greater than 1, suggesting that these variables exhibit nonlinear relationships with solid waste generation. Based on EDF values, the variables' contributions to the model rank as follows: EDV (8.759), IAV (8.082), DPAA (7.913), TPIE (7.826), PCO (7.257), MBRIE (5.989), IIPC (4.911), and PCGDP (4.335).

The adjusted R^2 value of the GAM model fitted in this study is 0.774, indicating that the model possesses good explanatory power for solid waste generation. Based on the

comprehensive analysis results, this GAM model effectively reveals the nonlinear relationships between various influencing factors and GISWG. It provides a reliable basis for further identifying key influencing factors and formulating targeted management strategies.

3.3. FACTORS INFLUENCING THE GENERATION OF GENERAL INDUSTRIAL SOLID WASTE

Figure 5a reveals a pronounced nonlinear relationship between PCGDP and GISWG. The EDF for the smoothing term is 4.335, passing the significance test ($p < 2 \times 10^{-16}$). The smoothing curve exhibits an EKC-style inverted U-shaped pattern: at lower PCGDP levels, solid waste generation rises rapidly with economic growth; however, once PCGDP crosses the inflection point of CNY 120,000 per person (approximately USD 17,028.04), the curve begins to flatten and even decline.

The findings reveal the phased evolution of environmental pressures under economic development. During the initial economic growth phase, industrial expansion serves as the primary driver, leading to synchronous increases in solid waste emissions and economic output. However, as development advances to higher levels, industrial restructuring and technological efficiency gains take center stage, gradually decoupling economic growth from solid waste generation. This validates the potential for synergistic pollution reduction and carbon emission cuts during high-quality development.

Figure 5b reveals a pronounced nonlinear relationship between IAV and GISWG. The EDF for its smoothing term reached 8.082 and passed the significance test ($p < 2 \times 10^{-16}$). Unlike the simple linear assumption, the curve exhibits a non-monotonic fluctuating upward trend overall: while industrial scale expansion generally increases solid waste generation, a distinct oscillatory pattern emerges in the marginal effect within the specific range of CNY 200–400 billion (approximately USD 28.38–56.76 billion). The confidence interval does not fully cross the zero axis at this point, confirming the statistical significance of this fluctuation.

This non-monotonic trajectory reveals the profound impact of internal heterogeneity within industrial structures on solid waste generation. As different stages of industrial development are often accompanied by alternating shifts in the proportion of heavy and light industries, coupled with substantial variations in pollution coefficients across sectors, the relationship between industrial value-added growth and solid waste generation does not maintain a constant positive correlation. Instead, it exhibits a fluctuating upward trend influenced by the dynamic interplay between the clean production levels of dominant industries and resource utilization efficiency.

Figure 5c reveals a pronounced nonlinear relationship between the MBRIE above designated size and GISWG. Its EDF is 5.989, with a p -value less than 2×10^{-16} . The curve exhibits a steep initial rise followed by a gradual flattening trend. Within the revenue range below CNY 10 trillion (approximately USD 1.42 trillion), revenue expansion drives solid waste generation in an almost linear fashion. However, once revenue exceeds this threshold, the curve's slope significantly diminishes, entering a plateau phase.

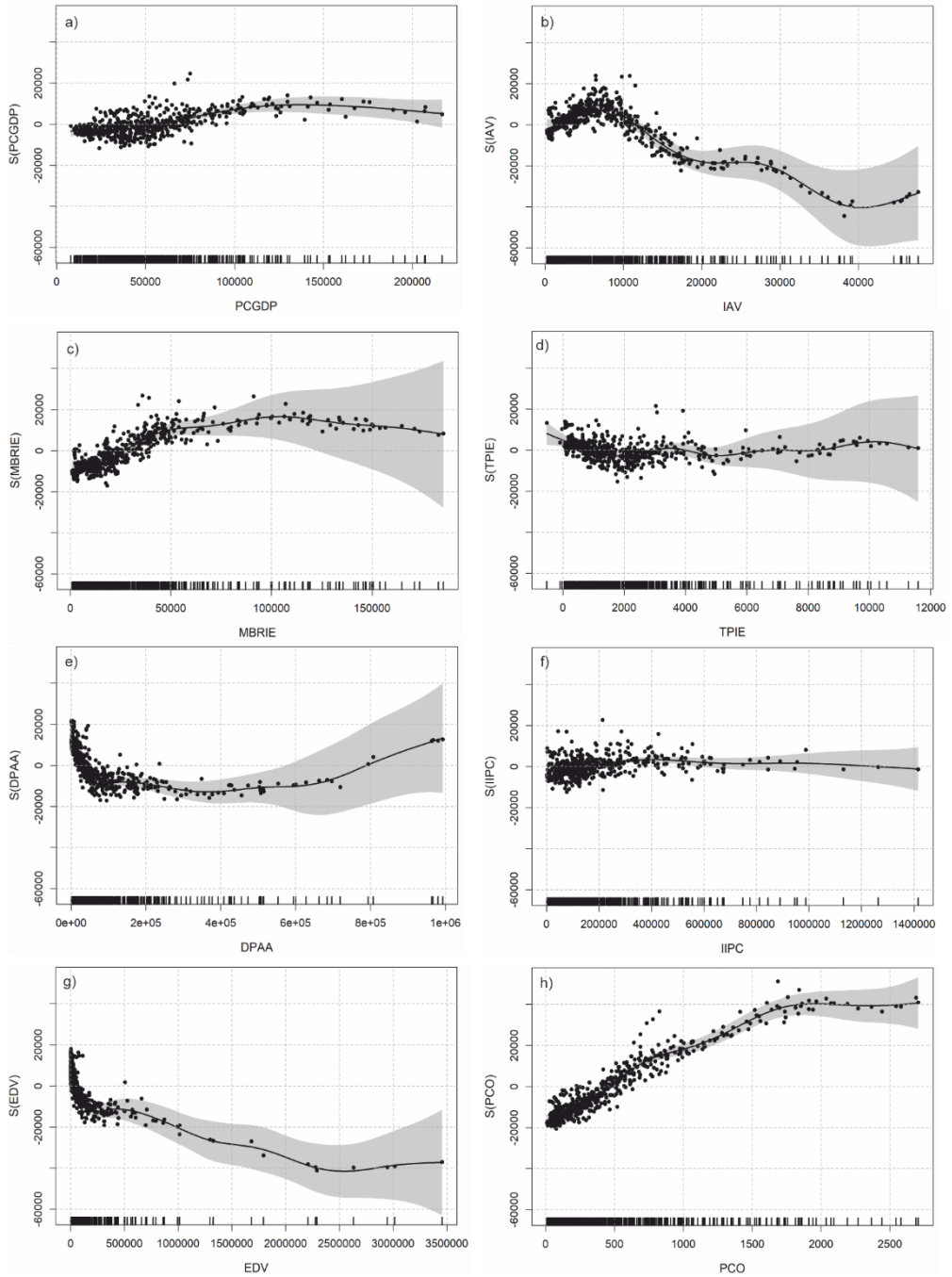


Fig. 5. GISWG as a function of socioeconomic and environmental variables; panels (a)–(h) discussed in the text

The results indicate that the driving effect of enterprise revenue scale on solid waste generation exhibits a pronounced diminishing marginal effect. During the initial expansion phase, the physical accumulation of production scale directly leads to a surge in waste. However, as enterprises grow to a certain scale, they often possess greater capital strength to implement intensive management and circular economy transformations. This gradually reduces the additional solid waste pressure per unit of revenue, reflecting the positive environmental externalities brought about by economies of scale.

Figure 5d reveals a significant nonlinear relationship between the TPIE above designated size and GISWG. Its EDF is 7.826, passing the significance test ($p = 0.0004$). The smoothed curve exhibits an oscillating upward trajectory: within the low-profit range (0–CNY 4000×100 million, approximately USD 0–56.76 billion), the curve fluctuates sharply with an ambiguous direction; however, once total profits surpass a higher threshold (> CNY 6000×100 million, approximately > USD 85.15 billion), the two variables display a relatively stable positive correlation trend.

This finding reveals a dual-impact mechanism of corporate profitability on environmental behavior. During periods of low or marginal profits, survival pressures may lead to unstable environmental investments, resulting in disorderly fluctuations in solid waste emissions. Conversely, when enterprises enter high-profit phases, although heightened production activity objectively increases the waste baseline, stable profit streams also signify the substantive establishment of production scale. At this stage, solid waste generation is primarily driven by production scale expansion.

Figure 5e shows that the relationship between DPAA and GISWG exhibits a U-shaped nonlinear pattern. Its EDF is 7.913, with a p -value less than 2×10^{-16} , indicating strong statistical significance. At lower levels of DPAA, the curve demonstrates a downward trend, suggesting that increases in innovation activity are associated with reductions in GISWG. However, as DPAA continues to increase beyond a certain level, the curve reverses and begins to rise, indicating a rebound in waste generation.

It should be noted that DPAA is used in this study as a proxy for overall regional innovation capacity, rather than a direct measure of environmentally oriented or green technological innovation. Therefore, the estimated effect reflects the combined influence of different types of innovation activities. In the early stages, increases in innovation may improve production efficiency, promote cleaner processes, and enhance resource utilization, thereby reducing solid waste intensity. However, at higher levels of innovation, intensified industrial agglomeration, expansion of high-end manufacturing, and scale enlargement may offset these efficiency gains. As a result, the scale effect may dominate, leading to an increase in total solid waste generation.

These findings suggest that innovation exerts a dual effect on GISWG, driven by the interaction between efficiency improvements and scale expansion. Consequently, an increase in the quantity of innovation alone may not guarantee sustained environmental improvement. From a policy perspective, greater emphasis should be placed on directing

innovation toward environmentally oriented technologies, such as green production processes and waste reduction techniques, in order to mitigate the potential rebound effects associated with large-scale industrial expansion.

Figure 5f shows that the relationship between completed IIPC and GISWG exhibits a significant nonlinear pattern. Its EDF is 4.911 and passes the significance test ($p = 1.86 \times 10^{-6}$). The curve displays a slight inverted U-shape with a generally low slope, showing a slight downward trend in the high investment range.

The findings indicate that end-of-pipe treatment investments exhibit significant lag and limitations in curbing solid waste generation at its source. Current remediation funding predominantly focuses on end-stage treatment of exhaust gases and wastewater, contributing little to solid waste reduction. While increased investment has moderately improved overall environmental management standards, merely boosting remediation funds is insufficient to achieve substantial reductions in solid waste generation. A shift in investment structure is essential – transitioning from end-of-pipe treatment to source prevention and clean production processes.

Figure 5g reveals a significant nonlinear relationship between EDV and GISWG. Its EDF reaches 8.759 and passes the significance test ($p < 2 \times 10^{-16}$). The curve exhibits a pattern of initial decline followed by fluctuation: during the early development phase of the express delivery industry, the curve drops sharply, then maintains relatively stable low-level oscillations within a vast volume range.

The findings suggest the complexity of interactions between logistics consumption and industrial production. The initial decline in the curve may reflect the substitution effect of EDV as a service-oriented indicator. Rapid growth in EDV typically accompanies industrial restructuring from heavy industry to modern services. This structural shift significantly reduces industrial waste intensity per unit of output. Furthermore, early standardization in packaging manufacturing has enhanced resource utilization efficiency. The subsequent stabilization of the curve indicates that despite the explosive growth of EDV, a mature industrial support system can now absorb new demand through economies of scale. Consequently, increased EDV no longer serves as the sole driver for explosive growth in industrial solid waste.

Figure 5h shows that PCO exhibits a significant nonlinear relationship with GISWG. The EDF for its smoothing term reaches 7.257 and passes the significance test ($p < 2 \times 10^{-16}$), indicating a highly nonlinear influence pattern. Specifically, the curve exhibits a pronounced upward trend followed by a plateau, a characteristic that concretely manifests the environmental Kuznets curve within consumption-driven industrial linkages. During the low PCO phase (0–2000), GISWG increased rapidly with rising PCO. After PCO crossed the threshold of approximately 2000, the growth curve flattened significantly, and the marginal propulsive effect of increased PCO weakened markedly.

The findings indicate that automobile consumption serves as a significant demand-side driver of industrial solid waste generation. As a durable consumer good with a long

supply chain and high interconnectivity, the increase in vehicle ownership directly stimulates capacity expansion in upstream high-waste industries such as steel, rubber, glass, and parts manufacturing. Against the backdrop of consumption upgrades, controlling waste emissions at the source within the automotive supply chain is crucial to curbing the growth of industrial solid waste.

4. CONCLUSIONS

This study employed GAM to analyze the socioeconomic drivers and nonlinear effects of GISWG across China's 30 provinces from 2007 to 2023. Key findings include: first, China's industrial solid waste generation exhibits distinct nonlinear evolution patterns. Temporally, it exhibits overall growth with fluctuating deceleration, reaching a negative growth inflection point in 2016. Spatially, it displays high heterogeneity, with heavy industrial provinces like Hebei, Shanxi, and Inner Mongolia leading in waste generation, while eastern and central regions significantly exceed western areas. Second, except for the municipal waste harmless treatment rate, all eight other drivers passed significance tests, and the degrees of freedom for smoothing terms exceeded 1, confirming the universal nonlinear nature of solid waste generation mechanisms. Third, the influence patterns of each factor exhibit distinct characteristics with clear thresholds and inflection points: PCGDP follows an inverted U-shaped curve, validating the environmental Kuznets curve; IAV shows oscillatory fluctuations; MBRIE diminishing marginal returns; enterprise total profits show oscillating growth, with solid waste increasing alongside scale expansion during high-profit phases; technological innovation demonstrates a U-shaped "first decrease, then increase" dual-channel effect; pollution control investment follows a weak inverted U-shape, indicating limited contribution of end-of-pipe treatment to source reduction; EDV first declines then stabilizes; PCO first rises then levels off.

Based on this, the following policy recommendations are proposed: first, implement differentiated regional controls. Provinces with high waste generation should strengthen clean production audits, while high-growth eastern provinces should enhance resource productivity assessments. Western regions must strictly control the transfer of high-energy-consuming industries. Second, decouple economic growth from solid waste generation. Developed provinces should explore pathways to peak total waste generation, while developing provinces should optimize industrial structures. Third, implement threshold-driven precision interventions: incorporate corporate revenue into key oversight metrics; establish resource efficiency benchmarks for mega-enterprises; guide green patent R&D to prevent innovation scale rebounds; reorient environmental investment toward source prevention and clean production; moderately regulate private vehicle growth; and refine express delivery packaging standards and recycling systems. These strategies provide empirical references for Zero-waste City development and comprehensive solid waste management.

Despite these policy implications, several limitations of this study should be acknowledged. First, the use of DPAA as a proxy for technological innovation may not adequately capture the environmental orientation of innovation activities, particularly green technological innovation. Second, although the GAM framework effectively identifies nonlinear relationships, it does not explicitly account for spatial spillover effects or inter-provincial dependencies, which may influence the distribution of industrial solid waste generation. Third, the analysis is conducted at the provincial level, which may mask intra-regional heterogeneity and firm-level dynamics. Future research could incorporate green patent indicators, spatial econometric techniques, and more disaggregated datasets to provide a more comprehensive understanding of the driving mechanisms of industrial solid waste generation.

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