Toward an orderly and efficient post-disaster humanitarian material donation system: a case study of the ‘9·5’ Luding earthquake

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Abstract

Purpose – This study aims to assess the orderliness of the humanitarian material donation system (HMDS) following the 2022 “9·5” Luding Earthquake in China, providing insights into improving disaster relief efficiency and promoting postdisaster recovery.

Design/methodology/approach – The orderliness of the HMDS is evaluated across three dimensions: donation input, donation output and donation environment. Correlation entropy and running entropy models are used to assess the system’s dynamics and to compare the performance of four donor types: government, enterprises, organizations and individuals.

Findings – The early emergency phase (the first 12 days after the earthquake) is characterized by disorder and repeated fluctuations, reflecting instability in donation activities. From Day 13 onward, the system transitions into a stable state, signaling the onset of recovery. The government plays a leading role in coordination, and enterprises serve as primary material suppliers, while organizations and individuals display higher uncertainty and spontaneity.

Originality/value – This study advances disaster management research by applying entropy-based models to dynamically assess the orderliness of HMDS. It extends theoretical understanding by linking entropy, orderliness and multiagent coordination and provides empirical evidence from a recent major earthquake. Practically, the findings highlight the differentiated roles of donor types and the importance of adaptive supply strategies in enhancing the efficiency and resilience of postdisaster relief systems.

Keywords Humanitarian donation, Orderliness assessment, Luding earthquake, Disaster response

Paper type Research paper

1. Introduction

The increasing frequency of weather and climate extremes (e.g. heatwaves, droughts) and natural hazards (e.g. earthquakes, wildfires) has posed unprecedented challenges to humanitarian relief systems worldwide in recent years (World Health Organization, 2023). As one of the countries most affected by meteorological and geological disasters, China reported more than 400 million affected individuals and direct economic losses exceeding US$13bn during 1990–2011 (Zhou *et al.*, 2013; Zhou *et al.*, 2015). Additionally, rapid urbanization and the resulting rise in population density have increased disaster exposure, making postdisaster response and recovery even more challenging. For example, in July 2021, record-breaking rainfall in Henan Province affected nearly 15 million people and left 398 dead or missing (People’s Daily, 2022; Peng and Zhang, 2024). In 2022, a severe drought across the Yangtze River Basin impacted 14 provinces, posing serious threats to agriculture, water supply and energy security (Wang *et al.*, 2023a). These severe disasters highlight the urgent need to establish more efficient and coordinated humanitarian response systems.

Material donation is a critical component of humanitarian response, providing an accessible channel for public participation during emergencies (Schlottke *et al.*, 2023; Imbriale *et al.*, 2024). According to the China Charity Donations Report 2020, both in-kind and monetary donations have shown sustained growth, with nongovernmental actors playing an increasingly significant role in emergency response efforts (China Development Brief, 2022). However, during the early stages of disaster response, humanitarian material donation systems (HMDSs) often suffer from operational

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disorder, poor coordination and inefficiencies (Burkart *et al.*, 2016). While in-kind donations can help rapidly replenish supplies, they also present challenges such as resource mismatches, logistical congestion and distribution delays. Relying solely on donation volume or logistical indicators is insufficient to capture the system's operational dynamics or to evaluate the coordination efficiency among diverse stakeholders.

System orderliness and entropy model offer new perspectives and methods for quantifying the effectiveness and coordination of HMDS. The concept of system orderliness derives from dissipative structure theory and synergetics, which explain how complex systems evolve from disorder to order through self-organization under external disturbances (Prigogine and Lefever, 1973; Hermann, 1989; Gong *et al.*, 2019). Within this framework, system orderliness is determined by two key dimensions: structural order and operational order. Structural order reflects the stability and consistency of system components, while operational order captures the degree of coordination and goal alignment during dynamic responses. The interaction between these dimensions directly shapes the system's capacity to reorganize and evolve from disorder toward order (Liu and Guo, 2023). Entropy further enhances this framework by offering a robust quantitative tool to track system transitions. Originally introduced in the 19th century to measure energy dissipation in physical systems (Clausius, 1879), and later refined in statistical physics, entropy is fundamentally a logarithmic measure of the number of microscopic states in a system: the greater the disorder, the more microstates are possible, and thus the higher the entropy (Boltzmann, 1877). In the 20th century, Shannon (1948) extended the concept to information theory, where entropy became a core metric of uncertainty in information sources. Given that HMDS is inherently complex and shaped by multiagent interactions, entropy, which captures both system disorder and information uncertainty, can effectively illuminate trends in coordination, structural stability and order evolution throughout the response process. Therefore, it offers significant potential for advancing the understanding and quantification of the operational dynamics and coordination capacity of HMDS.

Previous studies have examined donation systems from multiple perspectives and proposed various strategies to enhance their effectiveness. First, scholars have investigated the mechanisms of donation behavior, focusing on the motivations and patterns of different donors, including governments, corporations and civil society organizations (Islam *et al.*, 2013). Second, research has emphasized external factors shaping public participation, such as disaster type, geographical proximity and policy incentives (Kvarnlöf and Eriksson, 2024; Kawawaki, 2023; Tiefenbach and Kohlbacher, 2015). Third, at the operational level, studies have explored logistics strategies, such as route optimization and inventory control, to improve the efficiency of donation management (Özpolat *et al.*, 2014; Özpolat *et al.*, 2015; Chandes and Paché, 2010), alongside the use of social media and coordination mechanisms to strengthen mobilization and information integration (Islam *et al.*, 2013; Garber, 2012). In parallel, entropy-based models have been applied to the study of complex disasters and humanitarian systems as tools for characterizing uncertainty and assessing orderliness. Tavakkol *et al.* (2016) developed a multiobjective optimization framework based on information entropy for rapid postdisaster data filtering and analysis during the Nisqually earthquake in the USA; Renteria *et al.* (2021) applied cross-entropy and maximum entropy methods to conduct multidimensional classifications of disaster vulnerability in Colombia; Liu *et al.* (2025) constructed a symmetric entropy model to evaluate the dynamic stability of disaster chains in dam-break emergency planning; Aryatwijuka *et al.* (2023) analyzed the coordination and stability of large-scale logistics hubs under high uncertainty using entropy modeling; and Durmaz *et al.* (2021) introduced the concept of "negative entropy" to emphasize the role of continuous information and resource input in sustaining supply chain stability. Collectively, these studies have enriched understanding of HMDS by addressing behavioral drivers, contextual factors and operational strategies. However, the orderliness and coordination of multiagent interactions across different stages of HMDS remain underexplored.

This study develops a system orderliness assessment framework and a three-dimensional donation indicator system encompassing input, output and environment. By applying correlation entropy and running entropy, it quantitatively evaluates the dynamic orderliness of HMDS and addresses the following research questions: How does the orderliness of HMDS evolve during the postdisaster emergency phase? What are the differences in coordination patterns and behavioral responses among different donor types? Using the 6.8-magnitude earthquake that struck Luding County, Sichuan Province, China, on September 5, 2022 (hereafter the "9·5 Luding Earthquake"), as a case study, we assess the dynamic orderliness of the multiagent donation coordination system based on material donation records released by the local government. We further compare the behavioral characteristics and stability of different donor types. By applying entropy-based methods to a multiagent coordination system, this study contributes both theoretical insights and empirical tools for examining coordination processes in complex emergency settings.

The remainder of this paper is organized as follows: Section 2 introduces the data sources, indicator system and entropy model construction; Section 3 presents the main results; Section 4 discusses practical and theoretical implications, generalizability, limitations and future directions; and Section 5 concludes.

The contributions of this study fall into four main areas: *Methodologically*, it integrates the system orderliness framework with entropy modeling to propose a novel tool for assessing the order evolution of HMDS. *Theoretically*, it draws on complexity science and dissipative structure theory to conceptualize an "order-from-chaos" evolutionary pathway during the postdisaster emergency phase, thereby advancing understanding of collaborative evolution mechanisms in humanitarian studies. *Empirically*, using the 9·5 Luding Earthquake as a case study, the research compares the differentiated roles of governments, enterprises, organizations and individuals, highlighting patterns such as the relative stability of enterprise donations, the greater flexibility of organizational and individual contributions and the coordination-oriented role of government. *In application*, the proposed framework demonstrates strong potential for cross-contextual adaptation, offering practical guidance for collaborative governance across diverse disaster scenarios and institutional settings.

2. Methodology

2.1 Data collection

Luding County is located in southwestern China (Figure 1), covering an area of 2,165.35 km^2 with a population of 86,234 (Luding County Government, 2022). On September 5, 2022, a 6.8-magnitude earthquake struck the region, making it one of the most devastating natural hazards in China that year (Ministry of Emergency Management, 2023). The earthquake affected more than 540,000 people, resulted in 93 fatalities, damaged over 260,000 buildings and caused direct economic losses amounting to US$2bn (Shao *et al.*, 2024).

This study uses the “9·5” Luding Earthquake as a case study. The study period focuses on the postdisaster emergency response phase, as defined by the emergency command center, spanning from September 5 to October 3, 2022 (29 days). Data were obtained from five official releases of donation records issued by the local government on September 12, 17, 21, and 30 and October 1. The data set includes key information such as donation date, donating entity (government, enterprises, organizations or individuals), item names, quantities and units of measurement.

To ensure data quality and analytical accuracy, the raw data were systematically cleaned and formatted. Records were considered invalid and excluded if they met any of the following conditions:

- missing information on the donating entity or donation quantity;
- unclear item names; or
- inconsistent or ambiguous units of measurement.

All valid records were standardized into a format compatible with Python-based processing. A total of 1,291 valid donation entries were obtained, with the complete data set presented in Supplementary data 1. The overall research framework is illustrated in Figure 2.

2.2 Indicator system

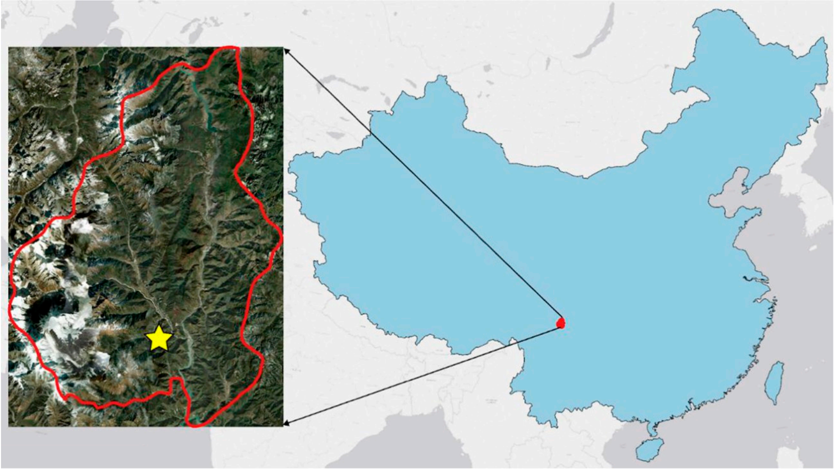
Relief materials differ in both function and emergency priority. Following previous research (Lu *et al.*, 2013), they were classified into four categories: life-sustaining materials (LSM), daily necessities (DN), medical materials (MM) and rescue equipment (RE). Based on this classification, we construct an orderliness evaluation system comprising eight quantitative indicators across three dimensions: donation input, donation output and donation environment. Table 1 summarizes each indicator’s definition, type and data source. Some indicators, such as per capita donation value and comprehensive search index, require preprocessing and formula-based calculation. Detailed descriptions of the relief material categories and indicator calculations are provided in Supplementary data 2.

2.3 Model construction

2.3.1 Correlation entropy

To assess the structural coupling among key variables within the HMDS, this study introduces correlation entropy as a measure of structural orderliness. Correlation entropy is derived from the gray correlation coefficient in gray system theory (Zhang *et al.*, 2024; Wang *et al.*, 2023b) and is used to quantify the closeness between each order parameter and its target state. Theoretically, stronger consistency and coordination among system indicators imply greater structural stability and higher orderliness, corresponding to lower correlation entropy values and stronger internal coupling. In model design, all indicators are treated as positive, meaning that higher values represent a more orderly system state. This assumption aligns with the logic of humanitarian relief: faster response, greater supply and more timely information imply higher system efficiency. For instance, increases in the number of donors, material diversity or frequency of government announcements typically indicate enhanced system coordination.

Figure 1 Geographic location of Luding County, Sichuan Province, China



Note(s): The star indicates the epicenter of the “9·5” Luding Earthquake
Source: Authors’ own work

Figure 2 Research framework for evaluating orderliness in the HMDS

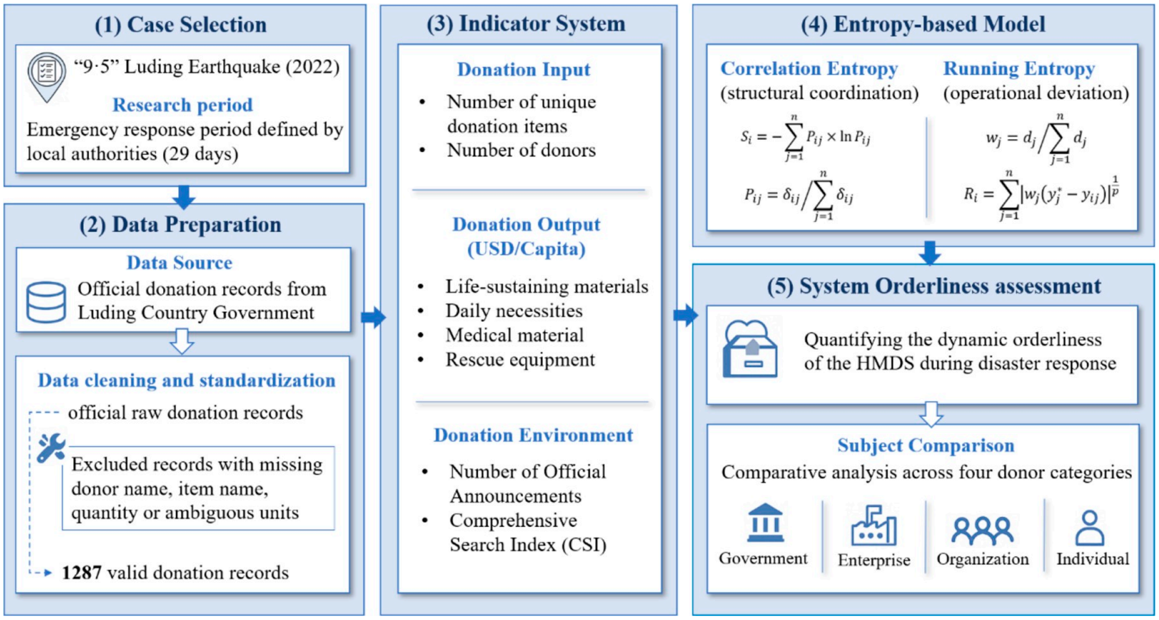


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Table 1 Description of indicators used for HMDS orderliness evaluation

Dimension	Indicator	Definition	Type	Data source
Donation input	Number of unique donation items	The number of distinct item types donated each day (e.g. milk, bread, water, tent = 4)	+	Calculated from official donation data
	Number of donors	The daily number of donors	+	
Donation output	LSM (US$/capita)	The daily per capita value of LSM/DN/MM/RE after the earthquake (US$)	+	Calculated from official donation data
	DN (US$/capita)		+	
	MM (US$/capita)		+	
	RE (US$/capita)		+	
Donation environment	Number of official announcements	The daily number of earthquake-related announcements by authorities	+	Calculated from the announcements of relevant governments (provincial, municipal and county government)
	Comprehensive search index (CSI)	The daily comprehensive search index for the keyword "Luding Earthquake"	+	Calculated from Baidu, Douyin and Toutiao Search Index

Source(s): Authors' own work

To define the ideal state of each system variable, this study sets the target value of each indicator as the maximum observed value during the study period, considering it the best attainable performance under emergency response conditions. Given the difficulty of specifying a theoretical optimum in disaster scenarios, using real-world extremes as comparative benchmarks offers greater practicality and adaptability. This approach has been applied in the evaluation of complex systems such as urban infrastructures and ecological networks (Liu *et al.*, 2018; Wang *et al.*, 2019). When combined with data cleaning and normalization, it helps reduce the risk of bias caused by outliers. The steps to calculate the correlation entropy are as follows:

Step 1: Based on the gray correlation analysis method, the correlation coefficient δ_{ij} of the indicator j on the ith day of the donation was calculated as follows:

$$\delta_{ij} = \frac{\min|y_j^* - y_j| + \rho \max|y_j^* - y_j|}{|y_j^* - y_{ij}| + \rho \max|y_j^* - y_j|} \tag{1}$$

Among them, $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n;$ y_j^* is the target value for each indicator, $\rho(0 < \rho < 1)$ is the resolution factor, usually taken as $\rho = 0.5$.

Step 2: According to the definition of gray correlation entropy and the mapping of the distribution of gray correlation coefficients, calculate the gray correlation entropy S_i:

$$S_i = -\sum_{j=1}^{n} P_{ij} \times \ln P_{ij} \quad (2)$$

$$P_{ij} = \delta_{ij} / \sum_{j=1}^{n} \delta_{ij} \quad (3)$$

Among them, $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n;$ P_{ij} is the weight of the correlation coefficient of the indicator jon the ith day.

2.3.2 Running entropy

To assess the operational efficiency and response order of HMDS during the emergency response, this study introduces running entropy to quantify the deviation between the system's actual operating state and its ideal state. Based on the principles of information entropy, this metric captures the uncertainty and dispersion in the distribution of internal system states (Shannon, 1948; Craig Herndon, 2021). When subsystems within the HMDS respond consistently and function smoothly, the information distribution becomes more concentrated, resulting in a lower entropy value and indicating a more orderly system. Conversely, greater inconsistency and heterogeneity among subsystems result in higher entropy values, reflecting a trend toward disorder. Lower running entropy thus suggests that the system is operating closer to its ideal state, with greater efficiency and stronger internal coordination. The steps to calculate running entropy are as follows:

Step 1: Calculate the information entropy e_j for the indicator j:

$$e_j = -k \sum_{i=1}^{m} \left(P'_{ij} \times \ln P'_{ij} \right) \quad (4)$$

$$P'_{ij} = Z_{ij} / \sum_{i=1}^{m} Z_{ij} \quad (5)$$

where $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n;$ $k = 1/\ln m$ is a constant related to each year, making $0 \le e_j \le 1$; P'_{ij} is the proportion of the indicator jin the ith year.

Step 2: Calculate the entropy weight w_j for the indicator j:

$$w_j = d_j / \sum_{j=1}^{n} d_j \quad (6)$$

$$d_j = 1 - e_j \quad (7)$$

Step 3: Calculate the running entropy R_i of the system:

$$R_i = \sum_{j=1}^{n} \left| w_j \left(y_j^* - y_{ij} \right) \right|^{\frac{1}{p}} \quad (8)$$

where $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n;$ d_j is the redundancy of information entropy, the larger d_j is, the more important the indicator is; in general, take $p = 1$(Hemming distance).

3. Result

3.1 Overall analysis of orderliness evaluation indicators

Figure 3 illustrates the temporal evolution of the number of donors and the number of unique donation items contributed by the government, enterprises, organizations and individuals following the earthquake. During the 29-day emergency relief phase, government donations were recorded on only 10 days, with both the number of donors and the variety of donation items being the lowest among the four donor types. Government donations peaked on Days 4–5 after the earthquake, primarily consisting of life-sustaining materials and daily necessities. However, from Day 6 onward, government donation activities declined rapidly, reflecting the government's primary role in disaster response as a coordinator and commander rather than as a major donor.

Enterprises emerged as the most significant donors in terms of both the variety of supplies and the number of donors, likely due to their financial strength, logistical capabilities and ability to mobilize large-scale resources quickly in response to urgent needs. The number of participating enterprises peaked at nearly 80, approximately 10 times that of the government and 3–4 times higher than that of organizations and individuals. Enterprise donations were most prominent during the first 2–6 days following the disaster, making substantial contributions across all categories of donated supplies. This highlights enterprises' efficiency in resource mobilization and their critical role during the emergency phase of disaster relief.

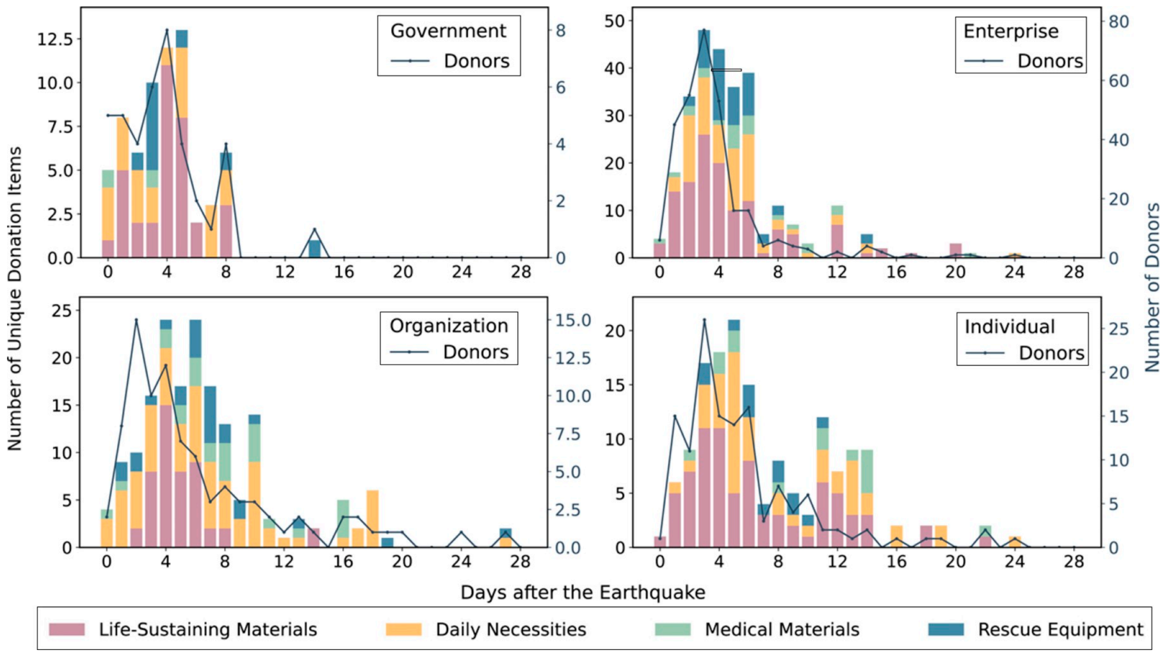
Compared with the government and enterprises, organizations and individuals exhibited a more sustained pattern of donations. Although their donation peaks also occurred within the initial 3–6 days, additional donation activities reappeared on Days 24 and 27. The number of individual donors exceeded that of organizational donors. Organizational donation activities began to decline rapidly after Day 9, while individual donations decreased significantly after Day 14. Nevertheless, sporadic individual donations continued during the later stages. Notably, organizations and individuals participated in donation activities on 20 of the 29 days, twice as many days as the government. This underscores the vital role of organizations and individuals in supporting long-term recovery efforts, as well as their flexibility and persistence in sustaining donation activities.

Figure 4 illustrates the daily per capita value of various types of humanitarian supplies following the earthquake, highlighting the dynamic nature of donation activities during disaster response efforts. Donations were predominantly concentrated during the initial rescue phase, spanning the first 10 days. On the day of the earthquake, the per capita value of medical materials in the affected areas was approximately US$20, underscoring the urgency of addressing critical survival needs during the early response phase.

During this period, life-sustaining materials and essential daily necessities accounted for the majority of the donation value. By Day 9, the per capita value of daily necessities had reached nearly US$50, potentially indicating issues of resource redundancy. In contrast, the per capita value of rescue equipment remained consistently low, likely reflecting the specialized nature and limited demand for such resources.

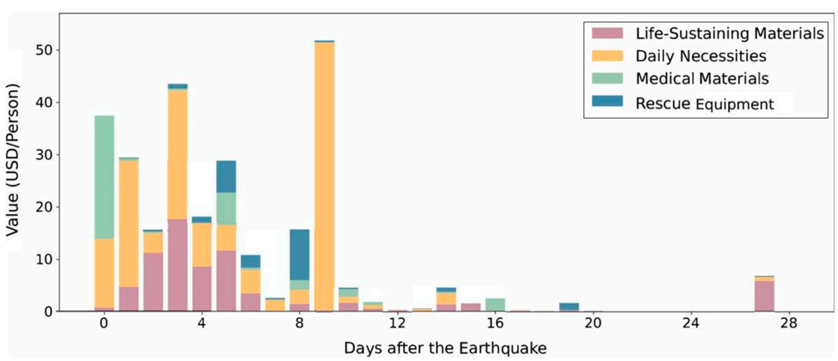
From the 10th day onward, the per capita value of donations declined sharply, marking the transition from the emergency response phase to the recovery phase. During this time, the per capita value of all supply categories consistently remained

Figure 3 Daily changes in the number of unique donation items and number of donors after the earthquake



Source: Authors' own work

Figure 4 Daily changes in the per capita value of different relief materials (US$) after the earthquake



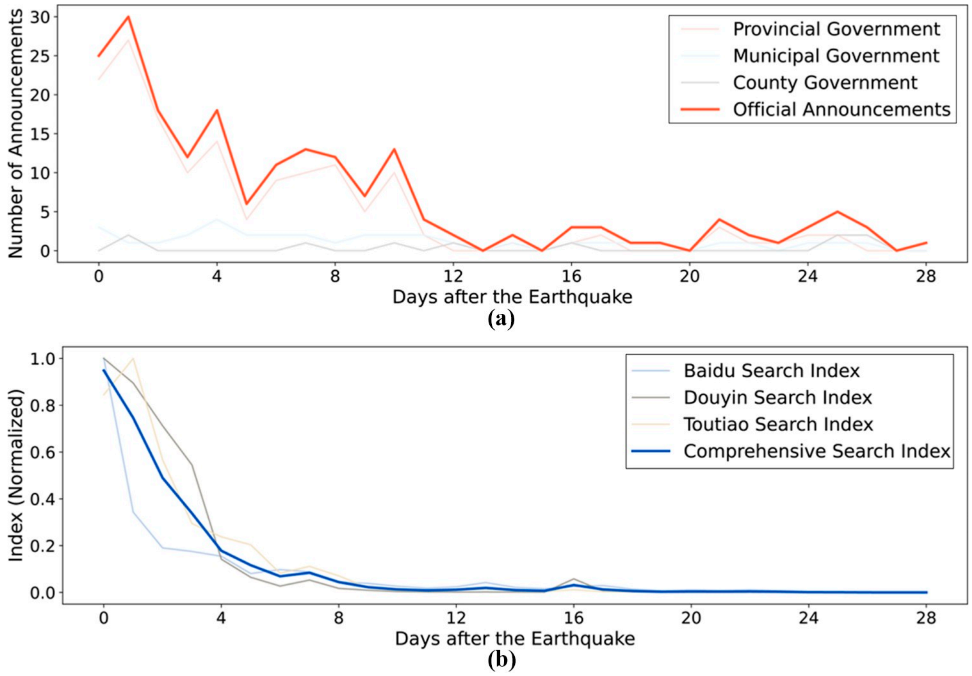
Source: Authors' own work

below US$10, with donation activities becoming increasingly sporadic. This temporal trend highlights the critical need for intensive supply support during the initial response phase and the subsequent tapering of donations as recovery progresses. The observed pattern aligns with established disaster relief strategies, emphasizing the importance of flexibility and adaptability in humanitarian supply chains.

Figure 5(a) illustrates the total number of announcements issued by government entities (at the provincial, municipal and county levels) following the earthquake (red line). On the first day after the earthquake, the provincial government issued the highest number of announcements. During the initial 10 days, provincial government announcements dominated, reflecting their immediate and coordinated response as well as their leadership role in disaster relief efforts. In contrast, announcements from municipal and county governments were significantly fewer, indicating their more localized or supportive roles in public communication. From the 11th day onward, the number of announcements declined sharply and remained low throughout the later stages, likely reflecting a reduced need for emergency public communication as the situation stabilized.

Figure 5(b) presents the comprehensive search index (CSI), calculated based on data from three major media platforms: Baidu, Douyin and Toutiao. The CSI peaked on the day of the earthquake, indicating a surge in public interest in disaster-related information. Thereafter, the CSI steadily declined, reaching very low levels by the 8th day, mirroring the trend observed in official announcements. Notably, two minor spikes in the CSI occurred on the 7th and 16th days after the

Figure 5 Daily changes in official announcements and comprehensive search index after the earthquake



Source: Authors' own work

earthquake, corresponding to the release of updated casualty reports on the 7th day and the successful rescue of an individual missing for 17 days on the 16th day, both of which temporarily reignited public attention.

A high degree of temporal consistency was observed between the trends in the number of official announcements and the CSI. As government announcements decreased, public search activity also declined, suggesting that official communications played a critical role in shaping public attention and information-seeking behavior. This consistency underscores the importance of coordinated communication strategies during disaster response efforts.

3.2 Entropy change of humanitarian material donation system

Figure 6 illustrates the dynamic changes in system entropy and correlation coefficients of the HMDS following the earthquake. As shown in Figure 6(a), the correlation entropy of the HMDS exhibited repeated fluctuations during the first 11 days before stabilizing around Day 12. Referring to the changes in correlation coefficients presented in Figure 6(c), on the third day after the earthquake, the correlation coefficients of key indicators, such as the number of unique donation items, the number of donors, life-sustaining materials (US$/capita) and daily necessities (US$/capita), increased significantly. This surge enhanced the internal connectivity of the system, making its structure more orderly and contributing to the primary cause of the decline in correlation entropy. Similarly, on the eighth and ninth days, sharp increases in the correlation coefficients of daily necessities (US$/capita) and rescue equipment (US$/capita) further promoted structural order within the system, leading to another reduction in correlation entropy. From the 12th day onward, the correlation coefficients of various indicators tended to stabilize, indicating that the system's structure had achieved a new state of equilibrium.

According to Figure 6(b), the running entropy of the HMDS showed a fluctuating upward trend after the disaster, stabilizing around Day 13. The indicator weights derived from the measurement of running entropy reveal the extent to which each indicator influenced system efficiency. Using the natural breaks method, the influence levels of these indicators were classified into three grades, as shown in Table 2. Indicators such as medical materials (US$/capita), rescue equipment (US$/capita), daily necessities (US$/capita) and the CSI were identified as having a significant impact on system efficiency. For instance, the marked increase in daily necessities on Day 3 and the substantial support from rescue equipment on Day 8 led to notable reductions in running entropy. These reductions helped stabilize the donation system and improve its operational efficiency. From Day 12 onward, the running entropy remained within a stable range, although sporadic donation activities during the later stages caused occasional minor fluctuations.

Based on the changes in correlation entropy and running entropy of the HMDS following the earthquake, the development of the HMDS can be divided into two phases: the chaotic phase (Days 0–12) and the stabilization phase (Days 13–28). During the chaotic phase, the entropy of the HMDS experienced frequent and significant fluctuations, reflecting repeated transitions between disorder and order. This highlights the characteristics of the early disaster response, marked by urgent demands and insufficient coordination. As the system transitioned into the stabilization phase, the entropy of the HMDS tended to stabilize, with a significantly reduced

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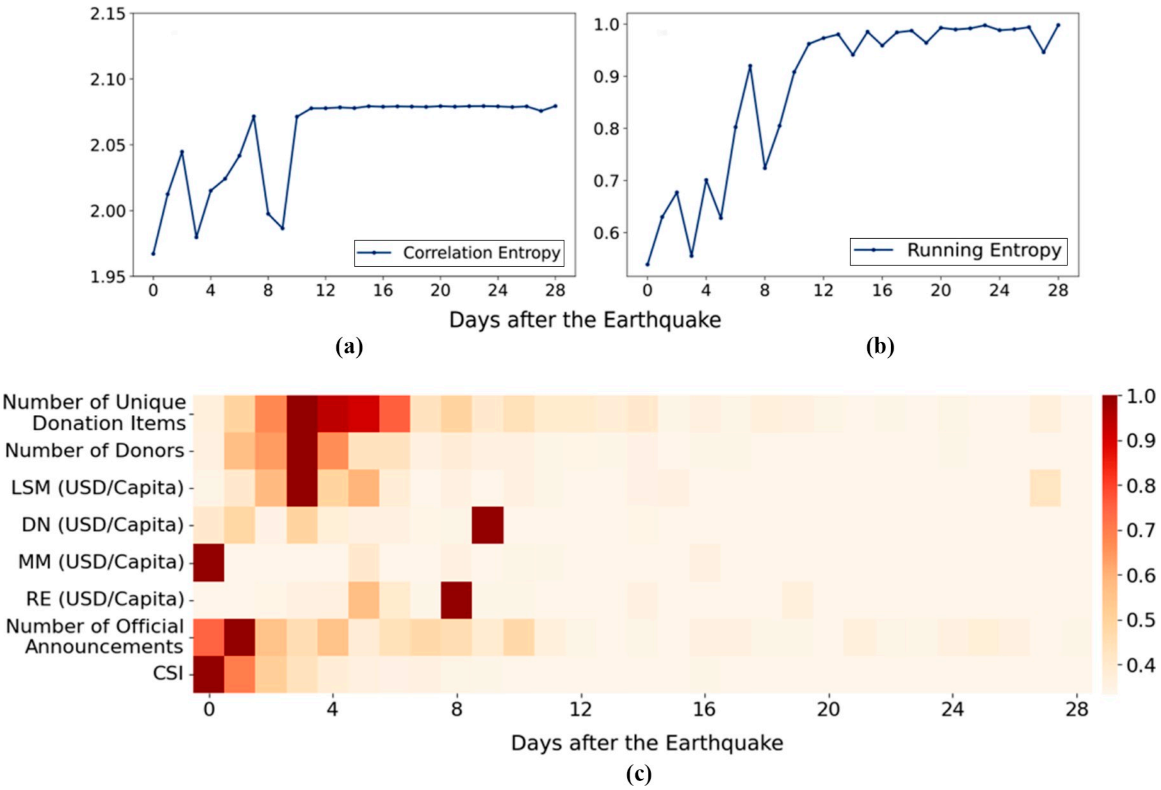
Figure 6 Daily changes in correlation entropy (a), running entropy (b) and correlation coefficients (c) of HMDS after the earthquake



Source: Authors' own work

Table 2 Weights and impact levels of indicators in HMDS

Impact level	Weight range	Indicator	Weight
High	(0.1652, 0.2074)	MM (US$/capita)	0.2073
Medium	(0.1197, 0.1652)	RE (US$/capita)	0.1652
		DN (US$/capita)	0.1450
		CSI	0.1405
Low	(0.0595, 0.1197)	LSM (US$/capita)	0.1196
		Number of donors	0.1028
		Number of official announcements	0.0598
		Number of unique donation items	0.0596

Source(s): Authors' own work

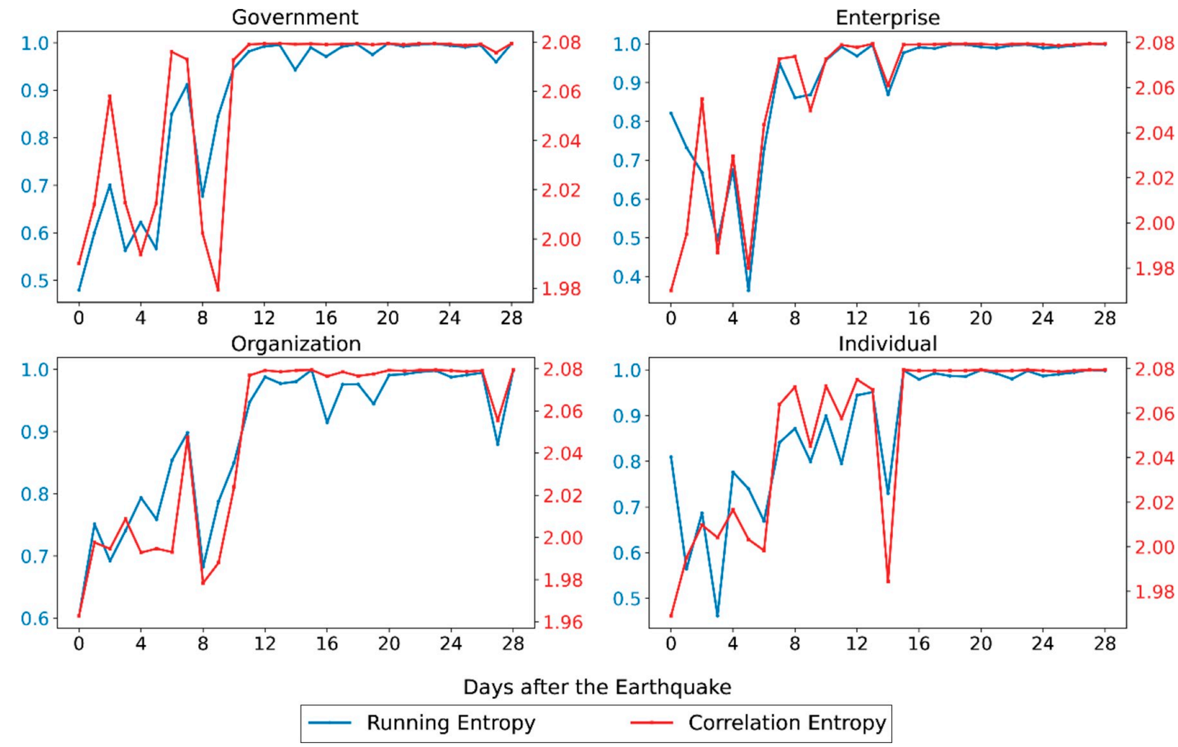
frequency and amplitude of fluctuations. This indicates that the system achieved a new state of ordered equilibrium, signifying a shift from the initial disaster response to the later recovery stage, during which the HMDS developed in an orderly manner.

3.3 Comparative evolution of orderliness under different donors

To further explore the evolutionary patterns of orderliness in the HMDS under the leadership of different donors, Figure 7 illustrates the trends in running entropy and correlation entropy for systems led by government, enterprises, organizations and individuals. The HMDS led by different types of actors exhibited notable differences in the evolution of system orderliness. The government-led HMDS experienced substantial fluctuations during the first 10 days, reflecting high coordination pressure in source mobilization and multistakeholder collaboration during the early stage of the disaster. As centralized command mechanisms were gradually implemented, systemic disorder diminished rapidly and operational order stabilized, highlighting the government's strong capacity to integrate resources and restore system order.

The enterprise-led HMDS exhibited significant fluctuations during the first week, followed by a trend toward stabilization. The initial surge in donations may have been driven by corporate social responsibility commitments and brand

Figure 7 Daily changes in correlation entropy and running entropy of HMDS under different donor types after the earthquake



Source: Authors' own work

reputation incentives, leading to concentrated contributions shortly after the disaster. The subsequent stability reflects enterprises' strong capabilities in resource allocation and professional operations in procurement and supply chain management. Their standardized organizational structures allow enterprises to achieve greater coordination and adaptability within the system.

In comparison, the organization-led HMDS experienced a slightly delayed stabilization. Early-stage fluctuations reflect a strong dependence on disaster information and policy guidance, indicating that organizational donation decisions often require both internal consensus and external coordination. As interorganizational collaboration improved and operational frameworks were established, the system gradually stabilized. Occasional fluctuations in the later stages suggest a degree of uncertainty in organizational activities.

Among the four donor types, the individual-led HMDS demonstrated the highest level of instability. This reflects individuals' high sensitivity to rapidly evolving disaster needs and information flows, as well as the spontaneous and unpredictable nature of personal donations. Starting around Day 16, fluctuations began to subside, possibly due to the influence of external coordination and government guidance, which may have helped reduce the randomness of individual donation behavior.

4. Discussion

4.1 HMDS characteristics and practical implications

The government's core role in disaster response lies in serving as an "order builder" rather than a primary donor. As shown in Figure 3, its direct material contributions were limited, recording the fewest donation days, donor entities and types of donated items among the four donor categories. Nevertheless, entropy analysis demonstrates that the government-led HMDS reached a stable state almost in parallel with the overall system, underscoring its central role in resource integration and order restoration [Figures 6(a–b) and 7]. Moreover, the government dominated public communication by releasing authoritative information. The timing of official announcements closely mirrored CSI trends (Figure 5), indicating that government communication played a decisive role in directing public attention and shaping donation behavior. Thus, the government's primary value in disaster response is not as a major supplier of donations (Kapucu, 2009; Liu and Shi, 2023; Yang *et al.*, 2023) but in leveraging top-level design and authoritative information dissemination to guide the system's transition from chaos to order. This conclusion contrasts with the Nepal earthquake, where insufficient government coordination led to logistical disorder (Shrestha and Pathranarakul, 2018), and aligns with evidence from the Morocco earthquake, where the Whole-of-Government framework enabled the government to function effectively as both an "order builder" and a coordination hub (Malhouni and Mabrouki, 2025). The government's shift from a direct supplier to an order builder and information hub is therefore crucial for improving overall relief efficiency and strengthening system resilience (Kapucu and Van Wart, 2008).

Enterprises serve as the primary suppliers of relief materials. In the early stage of the disaster response, businesses leveraging their financial and logistical advantages emerged as the dominant donors, with participation levels far exceeding those of other actors (Figure 3). This finding is consistent with that of Lüttenberg *et al.* (2025), who observed that enterprises are more inclined to contribute resources than to assume coordination roles. The enterprise-led HMDS displayed a distinctive pattern, characterized by initial volatility followed by rapid stabilization (Figure 7). Prior studies attribute this early volatility to large-scale, high-visibility donations motivated by corporate social responsibility and brand reputation (Godfrey, 2005; Muller and Kräussl, 2011; Whittaker *et al.*, 2015; Irshad *et al.*, 2023). The subsequent rapid stabilization largely reflects enterprises' standardized organizational structures and professional supply chain management capabilities (Van Wassenhove, 2006; Shi, 2019; Fan *et al.*, 2024). Overall, this pattern underscores the nature of enterprise donations as a form of strategic philanthropy, closely aligned with business objectives (Porter and Kramer, 2002; Ji *et al.*, 2021). Accordingly, disaster management strategies should prioritize the efficient mobilization of corporate resources in the early response phase and the seamless integration of corporate logistical capabilities into the broader emergency response framework.

Organizations and individuals function as "enduring supporters," yet their behavior is highly contingent on information guidance. Organizational donations follow a slow-onset, long-duration pattern. As shown in Figure 3, organizations contributed little during the initial peak of the disaster, but their donation activities persisted until Day 27. This is consistent with prior studies indicating that organizations often prioritize equitable resource distribution and sustained community engagement over immediate response speed (Iizuka, 2018; Park and Yoon, 2022). Entropy analysis further reveals that the organization-led HMDS experienced several minor fluctuations in the later stages of the disaster (Figure 7), suggesting that their rhythm and stability are shaped by external conditions, internal coordination and the uncertainties of fundraising (Kapucu, 2016). In contrast, individual donations exhibit marked volatility. Their donation peaks closely mirror fluctuations in the CSI (Figures 3 and 5), lending support to the empathy-altruism hypothesis, which posits that individual giving is largely driven by media-induced empathy (Benthall, 1993; Batson, 2011). Public enthusiasm, however, tends to fade rapidly as media attention declines. Thus, although organizations and individuals demonstrate stronger long-term engagement, their fragmented and unstable behavior challenges the orderly functioning of the system. A management priority, therefore, is to harness authoritative and transparent information platforms to guide participation effectively, transforming flexibility and enthusiasm into well-coordinated actions that align with on-the-ground needs. Such efforts can help mitigate resource mismatches and enhance the overall efficiency of humanitarian response.

4.2 Theoretical implications

The core theoretical contribution of this study lies in introducing entropy theory into the dynamic analysis of HMDS and in establishing an analytical framework for assessing the evolution of system orderliness. Whereas prior studies have primarily applied entropy theory to static or predictive contexts, such as disaster risk assessment or logistics planning (Tavakkol *et al.*, 2016; Renteria *et al.*, 2021), this research examines the dynamic self-organization processes embedded within the system's internal structure. It uncovers the mechanisms through which a disaster response system transitions from chaotic disorder toward a more stable and ordered state. By doing so, this study extends the application of complexity science, dissipative structure theory and synergetics in disaster management, while also providing a new microlevel analytical lens for understanding complex adaptive systems, complementing existing macrolevel frameworks that often overlook the internal dynamics of system evolution.

4.3 Generalizability and transferability

The conclusions of this study are partially tied to the national context, including differences in institutional, cultural and technological factors across countries. At the institutional level, China typically adopts a centrally coordinated, government-led model of disaster response, designed to ensure rapid action and efficient resource allocation. The 2013 Lushan Earthquake exemplifies this approach (Lu and Xu, 2014). By contrast, countries such as the USA and Germany tend to rely on decentralized governance, where nongovernmental organizations (NGOs) and local community networks assumed lead roles. Although these systems often promote greater transparency, their initial response efficiency is relatively limited (Whittaker *et al.*, 2015; Schwarz *et al.*, 2023). In contexts where governmental capacity is limited or disasters are particularly severe, the international community frequently activates the "humanitarian cluster" model, jointly coordinated by United Nations agencies and NGOs (Durrance-Bagale *et al.*, 2020). Prior research underscores that governmental coordination capacity and institutional effectiveness are critical determinants of disaster response performance. Deficiencies in policy guidance, resource allocation or interagency collaboration can result in significant operational disarray (Shrestha and Pathranarakul, 2018). Moreover, effective governmental coordination not only enhances the short-term efficiency of donations and relief operations but also plays a pivotal role in shaping the long-term resilience and adaptability of disaster response systems (Kim *et al.*, 2022; Shakibaei *et al.*, 2024).

Cultural and technological factors also play a significant role in shaping donation behavior and logistics efficiency. In East Asian countries, where collective values are deeply embedded, donation activities often follow a "government call–public response" pattern (Miki, 2013). By contrast, Western societies place greater emphasis on individual autonomy, with social media platforms serving as key facilitators of personal donations. For instance, during the California wildfires, crowdfunding through platforms such as GoFundMe enabled large-scale public mobilization, underscoring the pivotal role of social media in postdisaster relief (The Guardian, 2025). Technological tools have likewise demonstrated substantial potential in disaster response. In the case of cyclone relief in Zimbabwe, the integration of mobile phones, social media platforms and drones significantly enhanced the effectiveness, efficiency and flexibility of relief operations (Eldon and Kondakhchyan, 2018; Chari and Novukela, 2023).

Given the high heterogeneity of disaster governance in terms of type, tempo and actor structure, the system orderliness analysis framework proposed in this study demonstrates applicability across diverse disaster scenarios. For "slow-onset" disasters such as hurricanes and floods, where early warnings are typically available, the framework can be used to trace the dynamic process through which social resources become progressively ordered following the issuance of warnings. It also enables comparative analysis of system entropy before and after the events. In cross-regional and cross-cultural contexts, the framework reveals patterns of system evolution under different governance models. For example, government-led response systems often achieve stabilization more quickly, whereas regions dependent on international aid and NGOs may display greater volatility and slower stabilization. In practical applications, contextual adaptation is essential. For instance, for information flow indicators, the China-specific CSI index can be substituted with platform metrics from X (formerly Twitter), Facebook or mainstream media coverage in other contexts. In summary, the entropy-based system orderliness framework is adaptable to a wide range of disaster types and governance models, providing methodological support for comparative studies of disaster response across different regions.

4.4 Limitations and future research

We acknowledge the following limitations in this study. First, some donation records were excluded from the analysis due to missing key fields, which may have influenced the completeness of the results. Future research could integrate multisource data and incorporate public perspectives to provide a more comprehensive understanding of the evolution of system orderliness. Second, the analysis focuses exclusively on in-kind donations and does not account for financial aid. Subsequent work could broaden the scope to examine the complementary relationship between material and cash donations and to evaluate their combined influence on the efficiency of postdisaster recovery.

Future studies could also extend the applicability of the proposed framework to different disaster types and regional contexts. Incorporating multisource data, such as social media activity and logistics tracking, would improve its ability to capture dynamic system behaviors. Furthermore, the integration of machine learning and system simulation techniques to identify supply–demand trends and optimize donation pathways could strengthen the resilience and adaptability of postdisaster donation governance.

5. Conclusions

Using the 2022 Luding Earthquake as a case study, this research develops a system orderliness evaluation framework that integrates correlation entropy and running entropy to capture the short-term dynamics of the HMDS during postdisaster emergency response. The framework assesses system orderliness across three dimensions: donation input, donation output and donation environment. Results show that the system experienced significant fluctuations during the first 12 days, reflecting a phase of "disorder–reorganization." From Day 13 onward, the system began to stabilize, marking a transition to the recovery phase. Comparative analysis reveals that government-led systems show clear advantages in centralized coordination and resource integration. Enterprise-led systems respond quickly to disaster demands but exhibit moderate volatility, likely due to supply chain constraints and cost considerations. In contrast, systems led by organizations and individuals show greater instability, largely driven by information flow, public opinion and emotional factors.

Ethics statement

The donation data used in this study were obtained from official donation records published by the Luding County Government. These records were released to ensure transparency in postdisaster relief efforts and are accessible through official government channels. To protect privacy, the analysis was conducted at an aggregate level. All individual donor names were anonymized, and no personally identifiable information was disclosed, analyzed or reported. Donor names for governments, enterprises and organizations were retained only when publicly disclosed in the original government releases. The use of publicly available secondary data complies with ethical standards for research involving nonsensitive and anonymized data sets.

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Supplementary material

The supplementary material for this article can be found online.

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