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Design of a Pneumatic Waste Collection System for Solid Waste Segregation at Railway Stations

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ABSTRACT

The pneumatic waste collection system (PWCS) is a safe, efficient, hygienic, and environmentally sustainable method for municipal solid waste (MSW) management. In alignment with national policies advocating a four-category waste classification system, this study addresses the integration of pneumatic conveying technology with source-separated waste collection. Based on the operational principles and equipment configuration of PWCS, and considering current waste generation patterns and composition at railway stations, two centralized collection schemes for classified waste were developed. Unlike conventional PWCS solutions, which are generally designed for mixed or single-stream waste collection, the proposed system enables four-category source separation and coordinated pneumatic transport through a shared pipeline network. These schemes incorporate both non-storage and storage-enabled waste inlet ports, which share a unified conveying pipeline, thereby enhancing system flexibility and efficiency. At the terminal end of the pneumatic system, three sets of gas-solid separation units, compaction devices, and collection containers are configured to achieve integrated four-category classification functions, including sorted input, segregated collection, categorized compaction, and classified transportation. In practical terms, the proposed schemes can reduce manual waste handling, improve sanitation conditions, and enhance collection efficiency in railway stations characterized by high passenger flows, limited operational space, and highly variable waste generation. This work provides a technical and design foundation for implementing a new model of waste classification and transportation, and offers valuable insights into infrastructure requirements for efficient waste recycling in large-scale residential and transport hubs.

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1. Introduction

The escalating volume of global waste, propelled by population growth, urbanization, and industrial expansion, has intensified the demand for advanced waste management solutions (DehghanChenary et al., 2025). Waste collection is a pivotal phase within the waste management lifecycle, with a direct and substantial impact on the overall environmental sustainability of the system (Punkkinen et al., 2012). Conventional waste collection methods, such as curbside manual pickup, prove increasingly inadequate in densely populated urban centers and major transportation hubs, where issues of operational inefficiency and secondary pollution are compounded by a heightened focus on achieving low-carbon sustainability (Punkkinen et al., 2012; Chàfer et al., 2019; Farré et al., 2023). These challenges have driven the adoption of pneumatic waste collection systems (PWCS), which are valued as a next-generation solution for their fully enclosed, automated, and odor-free operation. In addition to this core benefit, PWCS show potential for adaptation beyond their original urban settings (Laso et al., 2019) and can reduce the land footprint of waste collection infrastructure (Teerioja et al., 2012). A comparative assessment by Punkkinen et al. (2012) between a hypothetical PWCS and conventional door-to-door systems further affirmed the potential of PWCS in mitigating carbon emissions and pollution risks.

Concurrently, China's rapid advancement in railway infrastructure has led to the construction of numerous modern, intelligent, and environmentally sustainable high-speed rail (HSR) stations. This development, coupled with continuously rising passenger numbers, has resulted in a substantial increase in waste generation within stations and onboard trains (Lu, 2015). Field audits indicate that HSR waste is dominated by plastics, paper, textiles, glass, metals, and food residues, which can be grouped into recyclables, hazardous fractions, and residual waste (Shui and Huang, 2013; Wang et al., 2019). In alignment with national policies, there is a strong advocacy for the classified disposal, collection, transportation, and treatment of municipal solid waste (He et al., 2021; Peng et al., 2021; Shang et al., 2021). However, the prevailing waste management practices in HSR settings predominantly depend on manual sorting and open-container transportation, which are associated with low recovery rates for recyclables (approximately 20 %), issues like odor release, and elevated operational costs. These shortcomings represent significant gaps that are inconsistent with the "Green HSR" principles championed by Chinese policymakers (Kaza et al., 2018; Guo et al., 2021; Cui et al., 2022). PWCS can facilitate automated, enclosed waste transport with high efficiency, speed, and relatively low energy consumption (Yang et al., 2017; Klinzing, 2018), can facilitate automated, enclosed waste transport. This technology enhances processing efficiency, mitigates secondary pollution, and aligns with the imperatives of urban environmental protection and resource conservation (Xiao and Wang, 2024). The entire process, managed by computerized control systems, enables 24/7 fully automated and sealed collection (Zhou, 2006), which has led to the gradual application of PWCS in sectors such as railways, commerce, healthcare, and airports (Shui and Huang, 2013). To address this gap, this study proposes two centralized source-separation schemes tailored to the operational characteristics of railway stations. The system integrates non-storage and buffer-storage waste inlets that share a single conveying pipeline, and employs three terminal gas-solid separation-compaction units triggered by spectroscopic or weight-based signals to route recyclables, hazardous items, and residual waste into dedicated containers. Consequently, the proposed configuration integrates four waste-classification functions: sorted disposal, segregated collection, categorized compaction, and classified transportation (Zhu et al., 2021). This research provides a crucial technical and design framework for a new paradigm in waste management, holding significant value for engineering design and potential application within the railway sector and related industries.

Previous railway-oriented PWCS studies have mainly discussed the feasibility and general layout of enclosed pneumatic transport. However, limited attention has been paid to integrating source separation with peak-flow management and category-specific terminal handling within one shared pipeline. The present study therefore develops two railway-oriented operating modes-immediate conveyance and buffer storage-and couples them with category-dependent valve routing and dedicated terminal separation and compaction units. The contribution is primarily a system-level design framework. Its hydraulic, energy, environmental, and economic performance is preliminarily assessed by engineering calculations, while pilot-scale validation remains necessary.

2. Principle and advantages of the pneumatic waste conveying system

2.1. System principle

The core functions of a closed pneumatic waste-conveying system are the transport, separation, and centralized collection of solid waste, as schematically illustrated in Figure 1. The infrastructure comprises waste inlets, buried pipelines, diverter valves, gas-solid separators, compactors, containers, suction fans, deodorization units, ancillary valves, and a supervisory control system (Chen and Geng, 2014). The individual components adopted in this configuration, including waste inlets, conveying pipelines, diverter valves,

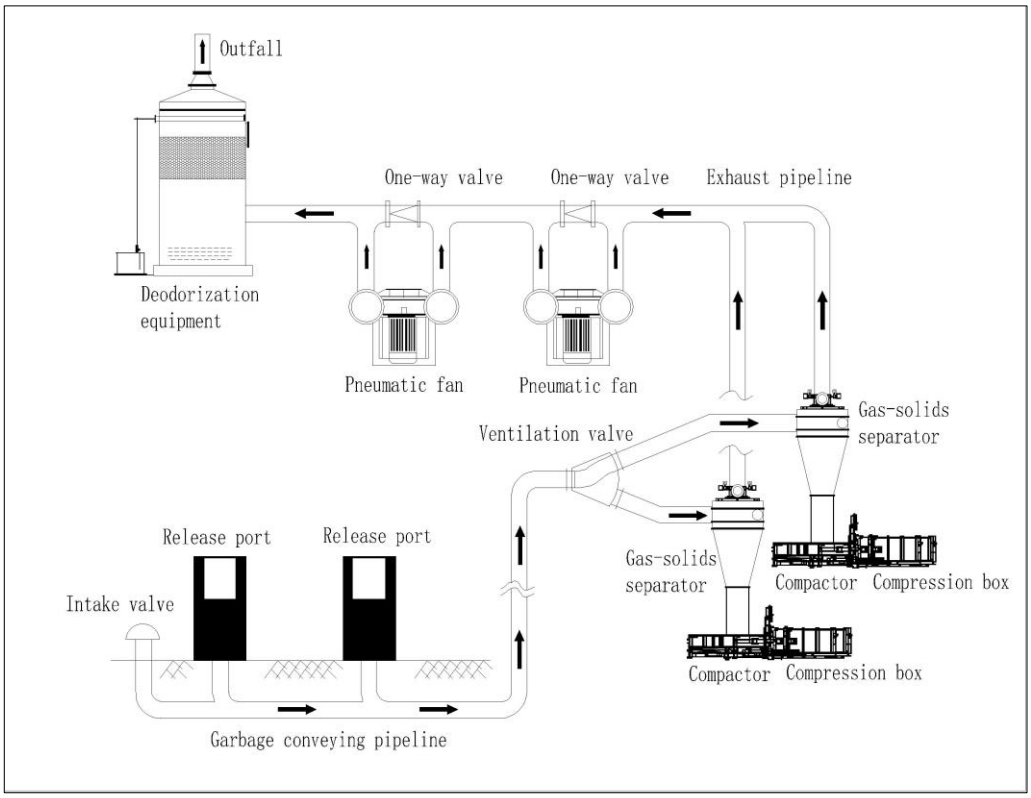


Figure 1. Working principle the pneumatic waste conveying system

gas-solid separators, compactors, suction fans, and exhaust-treatment units, are based on established PWCS engineering practice reported in previous studies. Upon disposal at an inlet, a control signal activates the fan, generating a high-velocity negative-pressure airflow that entrains the waste through the sealed pipeline network toward the central station. Following gas-solid separation, the compacted material is discharged into a dedicated container, while the exhaust air is treated by dust-removal and deodorization units prior to atmospheric release.

2.2. Advantages of the pneumatic waste conveying system

1. The enclosed pneumatic pipeline system inherently prevents secondary pollution by isolating waste from solar exposure, thereby effectively suppressing waste decomposition, the breeding of flies and mosquitoes, and the release of foul odors (Xu, 2010; Zhang et al., 2015). Furthermore, the conventional manual cart collection and the circulation of waste collection vehicles through platforms or waiting halls are eliminated, resulting in a significantly improved travel and working environment for passengers and railway staff (Li et al., 2015).
2. The implementation of automated conveyance technology, where waste is transported at speeds of 15-20 m/s by negative pressure and high-speed airflow, substantially improves transportation efficiency. This approach replaces traditional manual collection methods, leading to a marked reduction in both labor intensity and operational costs (Lin et al., 2006; Teerioja et al., 2012).
3. The collection and transfer station is typically located semi-underground and is equipped with containers capable of holding 10-15 tons of waste. The centralized configuration of collection facilities serves to reduce collection frequency while enhancing the overall efficiency of collection and transportation.
4. System design is designed to enable the centralized collection of sorted waste, which is conducive to subsequent recycling processes. Based on user disposal practices and waste categorization requirements, classified waste streams are transported via the pneumatic system to distinct collection units. This integrated process enables categorized disposal, collection, compaction, and transportation, thereby obviating the need for complex post-collection sorting and facilitating direct waste recycling and resource recovery.

3. Key equipment of the pneumatic waste conveying system

3.1. Inlet

The 450-mm inlet aperture is adopted as a preliminary screening dimension rather than as an experimentally optimized value. It is 50 mm smaller than the diameter of the conveying pipeline, thereby restricting the introduction of oversized objects and reducing the risk of pipeline blockage. Upon system activation, a high-speed, negative-pressure airflow is established within the pipeline.

Simultaneously, an air supply port provides a substantial additional thrust to the waste at the moment of discharge, imparting a high initial velocity and thereby effectively mitigating the risk of clogging. The inlet is equipped with a tri-color indicator light, where a yellow signal denotes a standby or queuing state, a green signal confirms that the airflow is sufficient to permit waste deposition, and a red signal indicates a system fault.

Figure 2 schematically illustrates the non-storage inlet. The assembly primarily consists of an air supply port and the main inlet body. Integrated into the inlet body are a lid-opening button, selection buttons for designating waste as recyclable, hazardous, or other, and a tri-color indicator light.

All categorized waste types are introduced sequentially through this single inlet. The routing of the waste to the corresponding collection container, according to its classification, is managed by controlling the position of the diverter valve. A key characteristic of this inlet design is the absence of an integrated storage function, allowing waste to be conveyed immediately after deposition.

Each classification button provides a discrete input to the local programmable logic controller (PLC) or remote input/output module. The selected category is transmitted to the supervisory controller, which first checks system availability and safety interlocks, commands the diverter valve to the corresponding terminal unit, and starts the suction fan.

Waste deposition is enabled only after valve-position feedback and the required negative pressure or air velocity are confirmed. At the end of the cycle, inlet-door, valve-position, and airflow signals are returned to the controller to complete the sequence and reset the inlet.

The schematic diagram of the waste inlet equipped with a storage function is illustrated in Figure 3. This assembly is primarily composed of an air supply port, the inlet housing, a storage hopper, and a pneumatic gate valve. A tri-color indicator light is integrated into the inlet housing.

Three distinct inlets are provided, each dedicated to the collection of a specific waste category: recyclable, hazardous, or other. Waste is temporarily stored within the hopper section of the respective inlet. Once the accumulated waste in the hopper reaches a predetermined level, the pneumatic gate valve is automatically opened. Subsequently, the stored waste is conveyed under system control to its corresponding container.

The required hopper volume is determined from the peak waste generation rate rather than from a fixed nominal value.

For each waste category, the preliminary design volume is calculated as $V_h \geq K_s\, q_{peak}\, t_b/\rho_b$, where q_{peak} is the category-specific peak mass generation rate, t_b is the maximum interval between conveying cycles, ρ_b is the loose bulk density, and K_s is a safety factor accounting for temporal variability and incomplete filling. Station-specific passenger-flow and waste-audit data are required for final sizing.

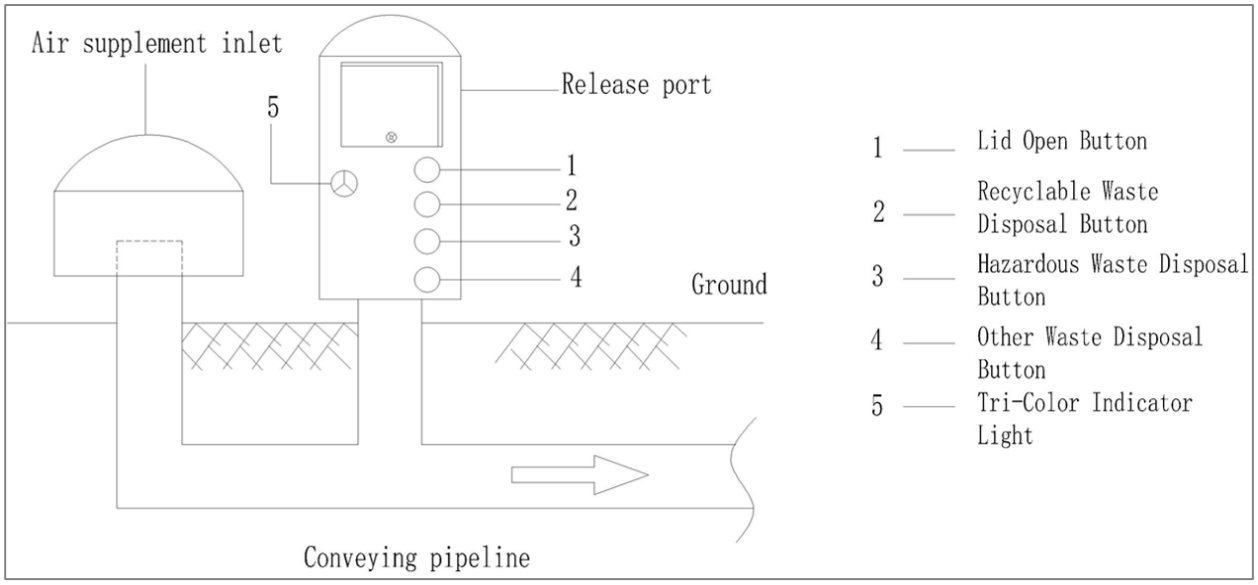


Figure 2. Schematic diagram of a non-storage waste inlet

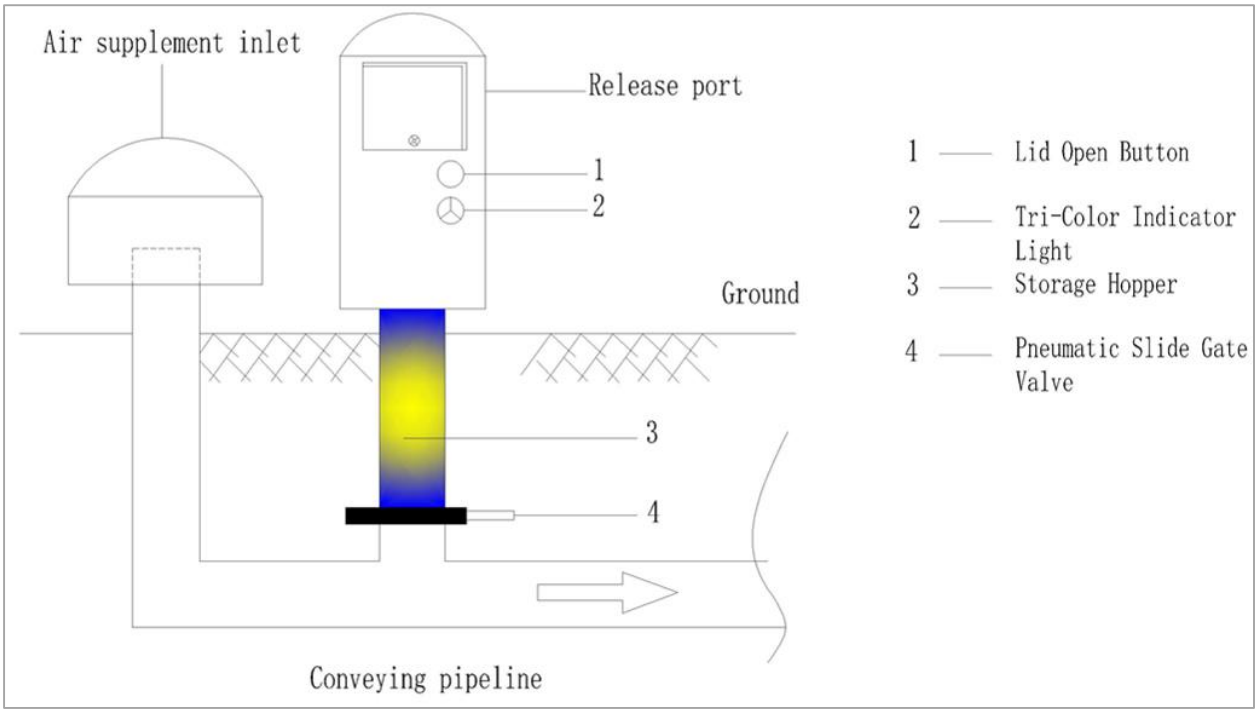


Figure 3. Schematic diagram of a storage-enabled waste inlet

3.2. Reversing valves

The diverter valve primarily consists of a cylinder system, an inlet, multiple outlets, a valve housing, and an internal rotating wire-reinforced hose. Upon activation of the pneumatic waste conveyance system, the cylinder is actuated by the automatic control system based on the waste category designated during disposal. This action drives the rotation of the internal hose, enabling the diverter valve to switch between three discharge ports. Consequently, the flow path of the waste and air mixture within the pipeline is altered, directing the waste stream toward the designated gas-solid separation unit.

3.3. Gas-solid separator

The gas-solid separator is a critical component for the successful and stable operation of the pneumatic waste conveyance system. It efficiently separates packaged waste and other solid materials from the high-speed air stream. During operation, a rotating screen within the separator is driven at high speed by an electric motor. This action dislodges lightweight materials, such as paper scraps and plastic bags, which are carried by the airflow, thereby separating the solid material from the gas phase. This process effectively prevents fine waste particles from entering the fan assembly through the air duct. Subsequently, when the system is halted, the dislodged lightweight plastics and other materials descend by gravity into the compactor unit situated below. Its performance should be characterized by the bulk-solid capture efficiency and pressure drop at the design airflow. In the preliminary engineering calculation, the separator pressure loss is included in the total system resistance together with straight-pipe friction, bends, valves, acceleration losses, and exhaust-treatment resistance (Yang, 2017). Final values must be obtained from manufacturer performance curves or pilot measurements under representative railway-waste loading.

3.4. Waste compaction equipment

The waste compaction unit comprises a compression main body (incorporating a compression head and cavity), a gate lifting mechanism, a hydraulic locking device, a push-pull container handling system, a hydraulic power unit, a control system, and a waste container. Its primary function is to compact loose waste into the container. During the compaction process, the compression system and the waste container are securely coupled via the hydraulic locking device. The compression head, fixed within the compression cavity, then pushes the waste into the container by means of a horizontal stroke. Once the container is filled to capacity, the compression system is automatically disengaged from the container. The filled container is subsequently transported to a landfill or other disposal facility by a hook-lift truck.

3.5. Dust and deodorization equipment

The exhaust gases from the pneumatic waste conveyance system may contain hydrogen sulfide,

ammonia, and volatile organic compounds (Li et al., 2016). Odorous substances are readily formed from organic waste through microbial activity within the pipeline and are transported to the terminal point along with the waste stream. The odor intensity originating from railway carriage waste is notably elevated during summer conditions. The primary function of the deodorization unit is to remove particulate matter and odorous components from the waste-laden air stream, ensuring discharge compliance with relevant national or local emission standards. Dust-laden and odorous air is drawn into the deodorization equipment by the pneumatic fan.

Through a process combining water scrubbing and chemical adsorption, particulate matter and impurities are transferred to the liquid phase. Concurrently, hydrogen sulfide and ammonia react with chemical agents during the spray cycle. The treated gas, upon meeting the required standards, is ultimately discharged through the exhaust outlet. Previous engineering applications have demonstrated effective removal of hydrogen sulfide, ammonia and particulate matter (He, 2015).

4. Design schemes for pneumatic waste collection at railway stations and on trains

Waste from railway stations and trains is generally categorized as recyclable, hazardous, or other waste. In accordance with the operational characteristics of railway stations, waste inlets are strategically positioned on platforms, in waiting halls, and in office areas. Based on the waste disposal practices of cleaning personnel, two centralized waste collection schemes were investigated.

The first scheme involves a non-storage disposal mode, wherein sorted waste is directly transported by cleaning personnel to the inlets located on platforms or in waiting halls. In this mode, interim storage at the inlet is not permitted, and the system is activated immediately to convey the sorted waste directly to the central collection station. The second scheme employs a storage-enabled disposal mode, whereby sorted waste is initially deposited into a storage hopper integrated into each inlet.

The system is automatically initiated to transport the waste from each hopper to the central collection station once the accumulated volume reaches a predetermined level.

4.1. Waste disposal in non-storage mode

Under the non-storage operational mode, sorted waste is transported by cleaning personnel to the designated inlets for immediate conveyance. Recyclable, hazardous, and other waste types are sequentially introduced through the same inlet. The system is then activated, automatically conveying the different waste streams through the pipeline network to their respective containers via the diverter valves, separators, and compaction units.

The system configuration for this mode primarily comprises an air inlet valve, non-storage inlets, a conveying pipeline network, diverter valves, gas-solid separators, compaction equipment (including compactors and containers), a pneumatic fan, deodorization units, and a central control system. The corresponding process flow diagram is illustrated in Figure 4.

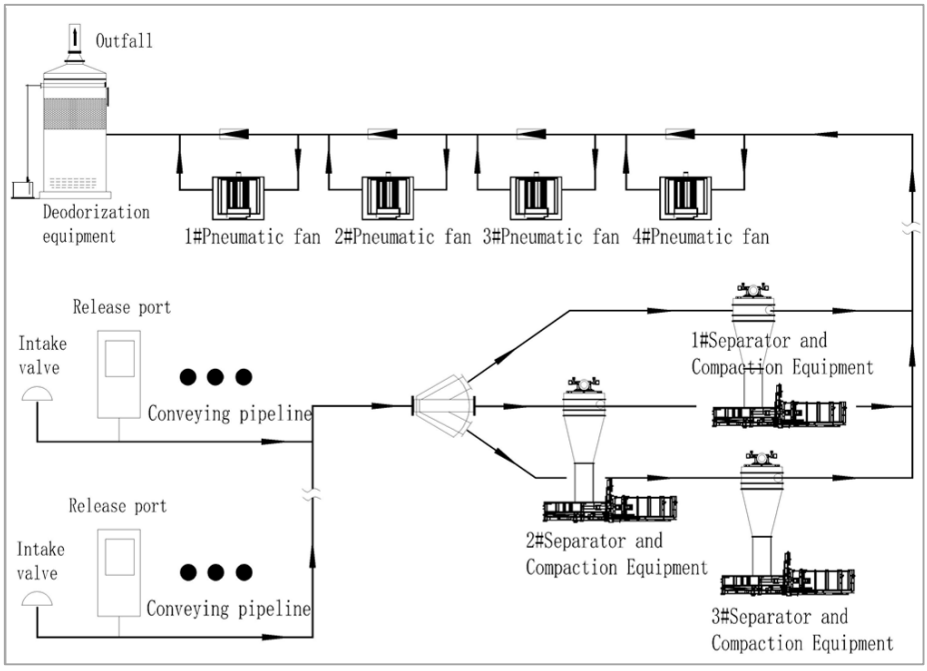


Figure 4. Process flow diagram of the pneumatic waste conveying system in non-storage mode

As illustrated in Figure 4, the inlet is designed without waste storage functionality. The three separation and compaction units (No. 1, No. 2, and No. 3) are designated for the collection of recyclable, hazardous, and other waste, respectively. The diverter valve is automatically switched to connect the pipeline to the required separation unit (1#, 2#, or 3#) as needed. Taking recyclable waste as an example, the operational cycle is initiated when cleaning personnel press the corresponding disposal button after delivering the waste to the inlet.

Upon activation, the corresponding system valve is opened, and the diverter valve is automatically positioned to connect the pipeline to the No. 1 separation and compaction unit. Once the air velocity within the system reaches the target value, recyclable waste is introduced into the inlet. The waste is then transported by the high-speed negative-pressure airflow through the diverter valve into the 1# separator, where it subsequently falls into the compactor, is compacted, and is finally stored in the attached container. A full operational cycle for recyclable waste is completed after all waste has been conveyed to the designated container.

The conveying air is discharged only after undergoing dust removal and deodorization to meet the required standards. When the No. 1 container reaches its capacity, it is removed from the station by a hook-lift sanitation vehicle. Hazardous and other waste streams are handled in an identical manner, being directed to the containers associated with the No. 2 and No. 3 separators, respectively.

The core components of this proposed system are the inlets and the diverter valve. All waste categories can be introduced through any inlet and are subsequently directed to their respective collection containers via the automated switching of the diverter valve.

1) Inlet: Each inlet is equipped with three control buttons corresponding to recyclable, hazardous, and other waste. Waste disposal, conveyance, and classification are initiated when the user presses the button corresponding to the waste category. The inlet dimensions are designed to accommodate waste bags with a maximum diameter of 450 mm, thereby preventing the entry of oversized items that could cause pipeline blockages. The inlet mechanism provides open/closed status signals, while the central control system monitors the start and completion of each waste disposal cycle.
2) Reversing valve: The diverter valve can be automatically switched to connect the conveying pipeline to any of the gas-solid separators, as directed by system commands, thereby establishing a continuous flow path to the designated separator, compactor, and container unit.

4.2. Garbage disposal with storage function

When interim storage of waste is permitted at the railway station, three dedicated inlets are installed on platforms and in waiting halls for the respective collection of recyclable, hazardous, and other waste categories. The waste is transported collectively to the central collection station once the accumulated volume reaches a predetermined level. The proposed system primarily comprises air inlet valves, storage-enabled inlets, a waste conveyance pipeline network, diverter valves, gas-solid separators, compaction equipment (including compactors and containers), a pneumatic fan, deodorization units, and a control system. The corresponding process flow is illustrated in Figure 5.

As depicted in Figure 5, all waste inlets are designed to temporarily store a specified volume of waste according to classification requirements. The separation and compaction units (No. 1, No. 2, and No. 3) are designated for the collection of recyclable, hazardous, and other waste, respectively. The diverter valve is automatically switched to connect the pipeline to the corresponding separator (No. 1, No. 2, or No. 3) as required. A typical operational sequence is initiated when the accumulated recyclable waste in Inlet 1-1 reaches a predetermined level, triggering a sensor signal. Upon activation, the diverter valve is automatically directed toward the No. 1 gas-solid separator, and the air induction fan is simultaneously started. The recyclable waste is then transported by high-speed negative-pressure airflow through the conveying pipeline and diverter valve into the No. 1 separator. Subsequently, the waste descends into the compactor, where it is compacted and discharged into the corresponding container. The conveying air is treated by dust-removal and deodorization systems to meet relevant standards before being discharged. Once the container is full, it is removed from the station by a hook-lift sanitation vehicle. Through this process, the three waste categories are automatically collected into their respective containers. The core of the proposed system centers on the inlets and the diverter valve. The inlets are designed with the following functional specifications: (1) Three distinct types of inlets are implemented, each equipped to temporarily store a predefined volume of designated waste. (2)Each inlet is capable of automatically detecting the waste level and transmitting corresponding start/stop signals to the control system. (3) A manual control button is also integrated into the inlet interface, enabling the initiation of a full operational cycle under special circumstances. (4) The inlet aperture is dimensioned to accommodate waste bags with a maximum diameter of 450 mm, thereby preventing pipeline blockages caused by oversized items. The diverter valve can be automatically switched to connect the conveying pipeline to any designated gas-solid separator based on system commands, thereby establishing a continuous flow path

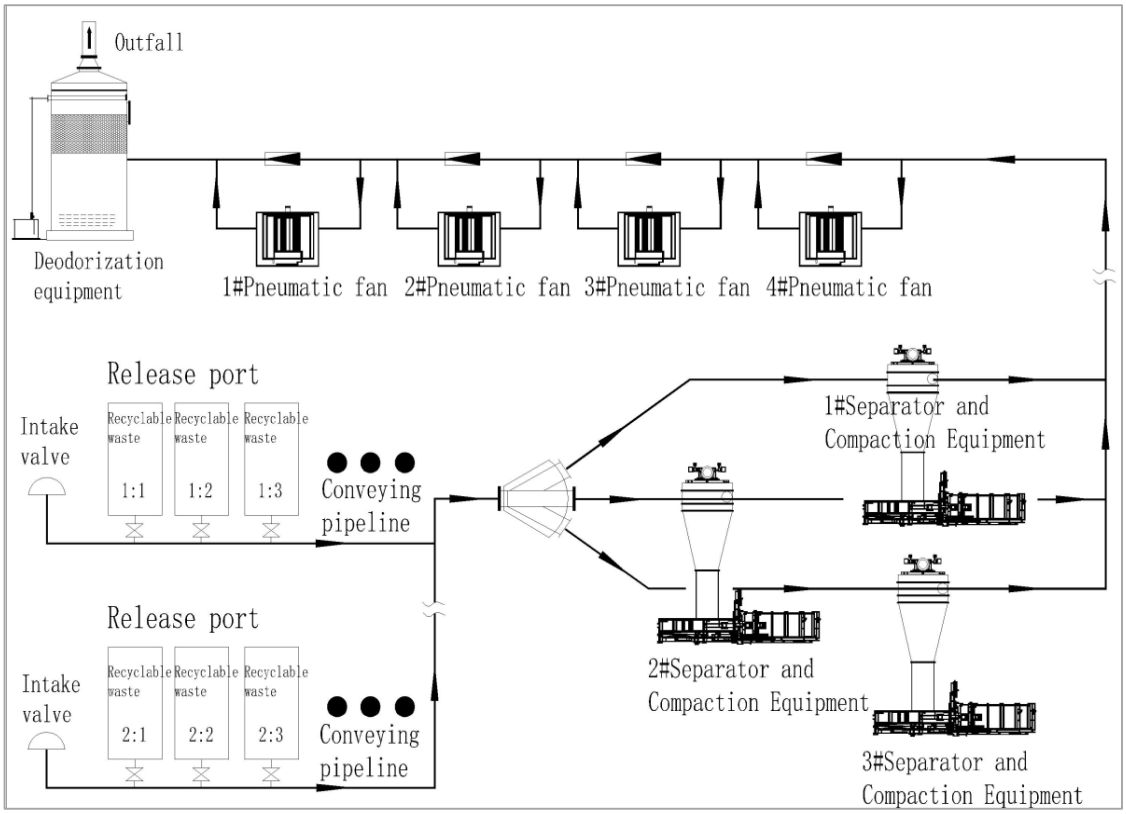


Figure 5. Process flow diagram of the pneumatic waste conveying system in storage-enabled mode

to the corresponding separator, compactor, and container unit.

Compared to the non-storage scheme, the storage-enabled approach is better suited for railway stations where waste generation is highly variable or concentrated. Temporary storage allows waste to be transported in batches once a predetermined level is reached. This approach reduces the number of system start-stop cycles during low-load periods and improves the system's ability to handle peak waste generation.

However, the additional equipment required for storage, such as storage hoppers, level sensors, and pneumatic valves, necessitates more maintenance and inspection. In contrast, the non-storage scheme transports waste immediately after it is generated, with a simpler design that requires less maintenance. Nevertheless, frequent individual transport cycles may still increase the overall frequency of system start-stop operations when waste is deposited intermittently. Therefore, the storage-enabled scheme is more appropriate for stations or areas with high or highly variable waste generation. In contrast, the non-storage approach is more suitable for locations with limited space, lower waste generation, or situations where immediate waste removal is required. Since this study focuses on system design, any quantitative comparisons of energy consumption and maintenance requirements will require detailed operational data specific to each station, as well as validation through pilot-scale tests.

5. Comparison of schemes

Compared with conventional station transportation systems at railway stations, pneumatic waste conveyance offers multiple advantages, including reduced labor intensity for sanitation personnel, improved waste collection and transportation efficiency, and shorter waste transport distances. Additionally, potential health risks from pathogenic microorganisms present in waste can be mitigated (Zhang et al., 2019). Previous studies reported that the unit operating cost and unit energy consumption associated with the pneumatic waste conveyance mode are lower, suggesting distinct environmental and social benefits (Teerioja et al., 2012; Yu et al., 2013). While pneumatic conveyance technology demonstrates considerable advantages for the clean transportation of bulk materials, it is concurrently associated with limitations such as high energy consumption, material degradation, and pipeline wear.

The adoption of dense-phase pneumatic conveying has been shown to effectively alleviate these shortcomings, representing a promising direction for technological advancement (Zhou et al., 2023). However, challenges remain, including reliance on proprietary technologies, high initial investment costs, a propensity for pipeline blockages at inlets, suboptimal deodorization performance, and the necessity for specialized personnel training due to the high level of system automation. Table 1 compares the characteristics of the different processes.

Table 1
Qualitative comparison of waste collection and transportation processes

Process	Conveying efficiency	Environmental impact	Application status	Advantages and disadvantages
Manual Cleaning and Transportation (Kaza et al., 2018; Elijah et al., 2023)	It depends on low manpower.	Exposed to the outside, large impact	Less	Low efficiency, waste spillage, and secondary pollution disrupt railway station traffic flow.
Closed Pipeline Collection and Transportation System (Brinkmann et al., 2016; Ramalho et al., 2025)	high	The whole process is closed, the impact is small	Technical difficulties still exist, the application range is small	Railway station traffic is efficient and emission-free, but the underlying technology is encumbered by proprietary patents.
Pneumatic Conveying (Punkkinen et al., 2011; Yu et al., 2013; Zaman and Lehmann, 2013; Elijah et al., 2023)	high	In the underground pipeline, harmful gases sink to the bottom, and the impact is small	The application is wide, and the waste is recycled or recycled	Although environmental load is reduced and both efficiency and janitor workload are lowered, refuse clogging remains frequent.

In addition to conveying efficiency and environmental impact, the economic and operational performance of a pneumatic waste collection system is influenced by capital investment, electricity consumption, maintenance requirements, collection capacity, and the potential reduction in greenhouse gas emissions. The initial investment of a PWCS is generally higher than that of conventional manual collection because of the installation of underground pipelines, pneumatic fans, separators, compactors, control devices, and exhaust-treatment equipment. However, the enclosed and automated system may provide long-term benefits by reducing manual handling, collection frequency, waste leakage, odor emissions, and interference with passenger circulation.

For the two schemes proposed in this study, the non-storage configuration has a simpler inlet structure and therefore involves fewer components requiring inspection and maintenance. However, immediate conveyance after each disposal operation may result in relatively frequent system start–stop cycles under intermittent waste generation conditions. The storage-enabled configuration requires additional storage hoppers, level sensors, and pneumatic gate valves, resulting in greater equipment and maintenance complexity. Nevertheless, batch transportation after a predetermined filling level is reached may improve system utilization during periods of concentrated or highly variable waste generation.

Annual operating costs, maintenance frequency, energy demand, greenhouse gas emissions, and collection capacity depend strongly on station size, passenger flow, waste generation rate, pipeline length, conveying frequency, fan efficiency, local electricity sources, and equipment maintenance strategies. As the proposed system has not yet been implemented at pilot or full scale, reliable quantitative values for these indicators cannot be provided at the present design stage. These indicators should be evaluated through station-specific engineering calculations, life-cycle assessment, and pilot-scale operational monitoring in future research.

Table 2 presents a qualitative comparison between the proposed pneumatic waste collection system and five representative systems reported in the literature. The comparison focuses on system configuration, waste classification capability, operating mode, and adaptability to railway-station conditions. Because the proposed system has not yet been validated through engineering calculations, numerical simulations, or pilot-scale operation, the characteristics presented in Table 2 should be regarded as potential design advantages rather than experimentally verified performance improvements. The comparison is structured across three key dimensions: the core functional characteristics of each reference system, their inherent limitations in meeting railway-specific operational requirements, and the corresponding enhancements introduced by the proposed system. The potential advantages presented in Table 2 are based on system configuration and operating principles rather than experimentally verified quantitative performance.

The economic and operational performance of the proposed system is affected by the initial investment in pipelines, fans, separators, compactors, control devices, and exhaust-treatment equipment, as well as by electricity consumption, maintenance requirements, labor costs, and collection frequency. Although the automated and enclosed configuration may reduce

Table 2
Qualitative comparison between the proposed design and representative systems reported in the literature

Literature Source & Core Features	Limitations of Literature S ystems	Advantages of My Designed System
Urban residential pneumatic system; n egative-pressure mixed conveyance; 12-18 % lower carbon footprint than manual collection (Punkkinen et al., 2012)	1. No waste sorting (mixed co nveyance only); 2. No peak a daptation (residential-only, pr one to pipeline congestion)	Adaptable to variable and concentrated waste gener ation through storage-enabled and non-storage inlet s; supports classified transport through a shared pip eline; the inlet restriction and supplementary airflo w are intended to reduce blockage risk.
Urban pneumatic vs. door-to-door sys tems; economic analysis (5-7 % highe r maintenance cost, 10 % lower labor cost) (Teerioja et al., 2012)	1. No sorting (no resource rec overy); 2. No railway cost opt imization (long-distance pipel ine, mixed waste)	Integrates classified collection and resource recove ry; may reduce manual handling; the modular confi guration can be adapted to different station areas.
Dense-phase conveying for coarse par ticles; 40 % lower energy, 60 % highe r equipment cost (Zhou et al., 2023)	1. Poor adaptability to railwa y dry waste (60-70% plastic/p aper); 2. No sorting (single-ty pe conveyance)	Adapted to heterogeneous railway waste and integ rates conveying, automatic routing, gas–solid separ ation, compaction, and classified collection.
Bangkok residential organic waste; m anual sorting; 35 % higher separation rate (community education) (Boonrod et al., 2015)	1. Low efficiency (30 min/ton manual sorting); 2. No closed conveying (high secondary po llution risk)	Reduces manual handling, provides enclosed transp ortation, and automatically routes different waste c ategories to dedicated terminal units.
Spanish historical center organic wast e; LCA-based; 15% lower GHG emis sions (Laso et al., 2019)	1. No multi-category sorting (organic-only); 2. No railway spatial/peak adaptation	Provides two operating modes for different station spaces and waste-generation patterns; batch convey ance may reduce unnecessary start–stop operations, but its energy and environmental performance requ ires further validation.

manual handling, waste leakage, odor emissions, and interference with passenger circulation, its annual operating cost and long-term economic benefits depend strongly on station size, pipeline length, waste generation rate, equipment operating time, and local energy and labor prices. Therefore, a reliable economic evaluation requires station-specific engineering data and pilot-scale operational monitoring.

6. Conclusions

The pneumatic pipeline conveyance system proposed for railway-station and train waste can reduce direct manual handling and secondary pollution during waste collection and transportation, while improving the hygienic conditions of the working environment. Based on the characteristics of railway waste generation and the operational practices of cleaning personnel, this study develops two source-separated collection schemes using non-storage and storage-enabled inlets. Through a shared pneumatic conveying pipeline, automatic diverter-valve control, and dedicated terminal separation and compaction units, recyclable, hazardous, and other waste streams can be directed to their corresponding containers, thereby providing a system-level design framework for classified disposal, enclosed transportation, separate collection, compaction, and subsequent resource recovery in railway stations. However, this study is limited to conceptual and system-level design, and the hydraulic and pneumatic performance of the pipeline network, separator efficiency, pressure losses, energy consumption, odor-removal performance, clogging frequency, operating costs, and greenhouse gas emissions have not yet been validated through numerical simulation, pilot-scale testing, or full-scale operation.

Practical implementation may also be affected by station layout, passenger flow, waste composition, peak waste generation, equipment maintenance, control-system reliability, and coordination with existing station facilities. Future research should therefore focus on station-specific engineering calculations, computational fluid dynamics simulations, optimization of pipeline and hopper dimensions, pilot-scale testing, long-term operational monitoring, life-cycle assessment, and techno-economic analysis to provide quantitative evidence for further system optimization and practical application.

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Projektovanje pneumatskog sistema za sakupljanje otpada radi razvrstavanja čvrstog otpada na železničkim stanicama

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I Z V O D

Pneumatski sistem za sakupljanje otpada (PWCS) predstavlja bezbedan, efikasan, higijenski i ekološki održiv način upravljanja komunalnim čvrstim otpadom. U skladu sa nacionalnim politikama kojima se promoviše sistem razvrstavanja otpada u četiri kategorije, u ovom radu razmatra se integracija tehnologije pneumatskog transporta sa odvojenim sakupljanjem otpada na mestu nastanka. Na osnovu principa rada i konfiguracije opreme pneumatskog sistema za sakupljanje otpada, a uzimajući u obzir postojeće obrasce nastajanja i sastav otpada na železničkim stanicama, razvijene su dve šeme centralizovanog sakupljanja razvrstanog otpada. Za razliku od konvencionalnih PWCS rešenja, koja su uglavnom projektovana za sakupljanje mešanog otpada ili pojedinačnih tokova otpada, predloženi sistem omogućava razvrstavanje otpada u četiri kategorije na mestu nastanka i koordinisani pneumatski transport kroz zajedničku mrežu cevovoda. Predložene šeme obuhvataju otvore za prijem otpada bez mogućnosti privremenog skladištenja i otvore za prijem otpada sa mogućnošću privremenog skladištenja, koji koriste zajednički transportni cevovod, čime se povećavaju fleksibilnost i efikasnost sistema. Na krajnjem delu pneumatskog sistema predviđene su tri grupe uređaja za razdvajanje gasovite i čvrste faze, uređaja za sabijanje otpada i kontejnera za sakupljanje, čime se omogućava integrisano razvrstavanje otpada u četiri kategorije, uključujući razvrstan prijem, odvojeno sakupljanje, sabijanje prema kategorijama i odvojeni transport otpada. Sa praktičnog aspekta, predložene šeme mogu smanjiti potrebu za ručnim rukovanjem otpadom, poboljšati higijenske uslove i povećati efikasnost sakupljanja otpada na železničkim stanicama koje karakterišu veliki protok putnika, ograničen raspoloživi prostor i izrazito promenljive količine nastalog otpada. Ovaj rad pruža tehničku i projektnu osnovu za primenu novog modela razvrstavanja i transporta otpada i daje značajne smernice u pogledu infrastrukturnih zahteva za efikasnu reciklažu otpada u velikim stambenim i saobraćajnim kompleksima.