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Review

Pneumatic Urban Waste Collection Systems: A Review

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Featured Application: Pneumatic urban waste collection systems for sustainable cities.

Abstract: Due to the increasing need for a more sustainable environment, the study of waste management strategies is increasing worldwide. Pneumatic urban waste collection is an alternative to conventional truck collection, especially in urban areas where there is a need for reducing traffic and pollution. In this study, the scientific literature on such automated waste collection systems (AWCSs) (also known as automated vacuum waste collection (AVWC) systems) is evaluated through a bibliometric analysis. The available scientific literature is found to be scarce, while there are several patents on the topic. The keywords used in the literature are mainly related to energy use, gas emissions, and the cost–benefit analysis. Moreover, the market status is presented and a summary of the environmental studies is provided. The active companies in the field are identified and a complete list of AWCSs is provided. Most of the scientific literature related to the environmental aspects of AWCSs uses the life cycle assessment (LCA) methodology to evaluate the performance of different case studies.

Keywords: pneumatic urban waste collection; automated waste collection; automated vacuum waste collection; sustainability; cities

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1. Introduction

According to the European Commission, waste represents a potentially enormous loss of resources, both in materials and energy [1]. Sustainable development in cities has municipal solid waste (MSW) as one of the main bottlenecks to address [2,3].

Moreover, waste management and disposal can have serious environmental impacts. In 2018, 5.2 tonnes of waste was generated per EU inhabitant; out of those, 38.5% of waste was landfilled and 37.9% was recycled. The economic activity with the highest contribution to waste generation in Europe is the construction and demolition sector, with 35.9%. Households generated 8.2% of the total waste in Europe in 2018 [1]. Worldwide, these numbers increase to 2 billion tonnes of MSW produced in 2021 and are expected to double by 2100 [4,5].

An important part of waste treatment is collection and transportation, which collects waste from households and transports them to transfer stations, processing facilities, or disposal sites [6,7]. Zhang et al. [2] stated that very few researchers paid attention to the collection and transport costs and the environmental effects of this step of waste treatment, since most researchers focussed on the final treatment. There are five common methods of waste collection: door-to-door collection, curbside/alley collection, dumping at a designated place, trespassing the property, and pneumatic collection [7–11]. Door-to-door collection is economic and convenient for residents, but it requires that somebody is at home at the time of pick up and is affected by terrain and climate; this system is mostly used in South Asian countries and cities such as Beijing in China and Nagoya in Japan. Curbside/alley collection is economic, independent, and convenient for separate collections, but transportation delays produce foul odours, and stray animals and flees gather due to food waste; this system is mostly used in developed countries in Europe and North America. Dumping at a designated place is the least expensive collection method with fewer labourers required, but it is inconvenient for citizens due to stray animals, it can rise public health issues (odours, pathogenic bacteria), and it is anaesthetic; it is used in low-income developing countries. Entering the property is convenient for residents and does not require any bins, but it is expensive, labour intensive, and requires the protection of privacy and properties; it is convenient for areas with small populations and sparse housing. Pneumatic collection is environmentally friendly, reduces traffic congestion, and requires less, although more qualified, labour. Nevertheless, it has a high initial investment, it is energy-expensive, and it has pipe blockage problems; it is adequate for highly developed urban areas.

Automated waste collection systems (AWCSs) offer citizens a modern and efficient method of waste collection. They improve the urban image, optimise the selective collection at the source, decrease the cost per tonne collected compared to conventional systems, and offer a smart service 24 h a day, 365 days a year.

Figure 1 shows a scheme of an AWCS. The AWCS has waste collection inlets inside and outside the buildings, which are connected to the pipeline network. The waste is pressed by fraction at the collection site to reduce the amount of air to be transported to the terminal. The terminal is usually at a municipal waste treatment plant where the waste is processed.

Figure 1. AWCS scheme. (1) Indoor inlets (on each floor), (2) outdoor inlets (with domestic door), (3) outdoor inlets (with professional door), (4) indoor inlets (on ground floor), (5) pipeline network, (6) separation and compaction unit (terminal), (7) blowers—de-pressurisation system, and (8) air treatment system. Source: URD.

The collection process starts by creating an airflow sucking the waste from the waste collection bins to the collection centre. The waste is stored at the collection centre in different fractions (i.e., paper, organics, plastic), and is later treated on-site or transported to the treatment plant if needed. Usually, the collection centre has a biofilter that controls odours and humidity.

2. Bibliometric Analysis

The database Scopus was used as a reference in the bibliometric analysis carried out in this paper. Compared to other databases such as Web of Science, this one includes a large number of documents about technological topics [12]. The query used was based on key terms related to the topic, which were "automated waste collection" and "vacuum waste collection". A total of 19 documents were found. Moreover, R-tool and the bibliometrix library were selected as the software used to perform the bibliometric analysis [13].

Figure 2 shows the trend in the number of publications in the period analysed between 2009 and 2022. It highlights the small number of existing scientific publications. This small number of publications related to vacuum waste collection shows a stark contrast with the number of publications related to the main alternate collection method, that is, using surface vehicles to pick up waste either from citizen's houses or from aggregated collection points (containers, underground containers, etc.). A simple search on the Scopus database of vehicle routing research for "waste collection" and "vehicle routing" (a search that, if refined, would yield several more results), produced 320 research studies. These studies ranged from 1974 [14] to more recent studies from 2023 [15]. These studies cover and profit from many technological advances, from ant colony optimisation algorithms [16] to neural networks [17]. This vehicle-based collection method also benefits from the application of research not specifically oriented toward waste collection, but to other uses of vehicles (mainly package delivery), and is a research topic well-studied in the literature. In fact, vehicle routing is a recurrent research problem in optimisation, problem-solving, and artificial intelligence research, and a quick search for "vehicle routing problem" or "VRP" (as it is often referred to in the literature) yields thousands of research studies (VRP is a generalisation of TSP, the travelling salesman problem, a problem studied since the mid-19th century).

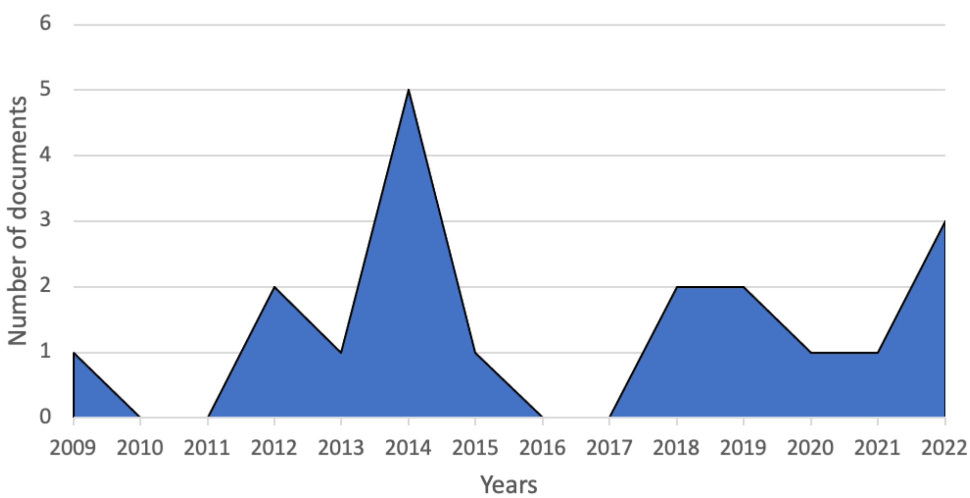

Figure 2. Annual scientific production between 2009 and 2022 using R-studio software and bibliometrix library of the automated waste collection system (AWCS) scientific literature found in Scopus.

Another facet of this anomalous lack of publications which indicates that, albeit the number of published articles is scarce, there is a serious research effort behind vacuum waste collection, is the number of filled patent applications, such as in [18–20], with some of these patents dating back to the 1970s [21].

Figure 3 presents a three-field plot which relates authors, keywords, and affiliations. The maximum number of each field was set to 20. The figure shows the relationship between 20 authors, 19 keywords, and 18 affiliations. The keywords "waste management" and "greenhouse gases" were the most used keywords. Moreover, the two affiliations that published the most documents about the topic were "University Transportation Research Center" at City College (New York, NY, USA) and "Universitat de Lleida" (Spain).

Figure 4 shows the most relevant sources on the topic during the period analysed. The source with the highest number of publications was "Waste Management" followed by "Environmental Modelling and Software", "Journal of Cleaner Production", and "Tunneling and Underground Space Technology".

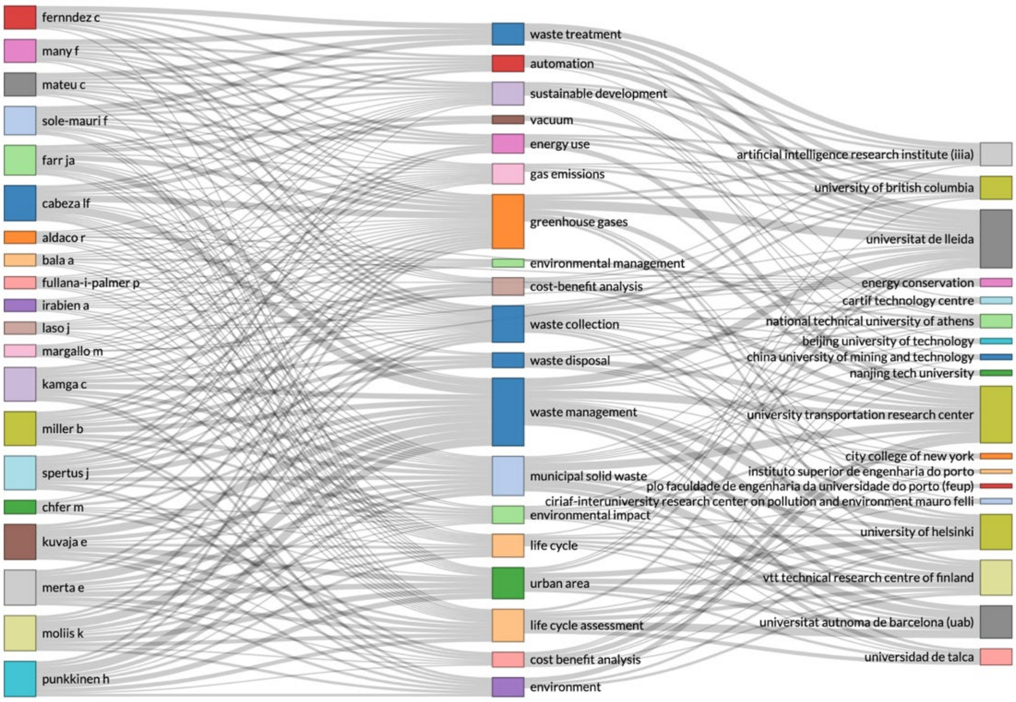

Figure 3. Three-field plot relating keywords, authors, and affiliations using R-studio software and bibliometrix library of the automated waste collection system (AWCS) scientific literature found in Scopus.

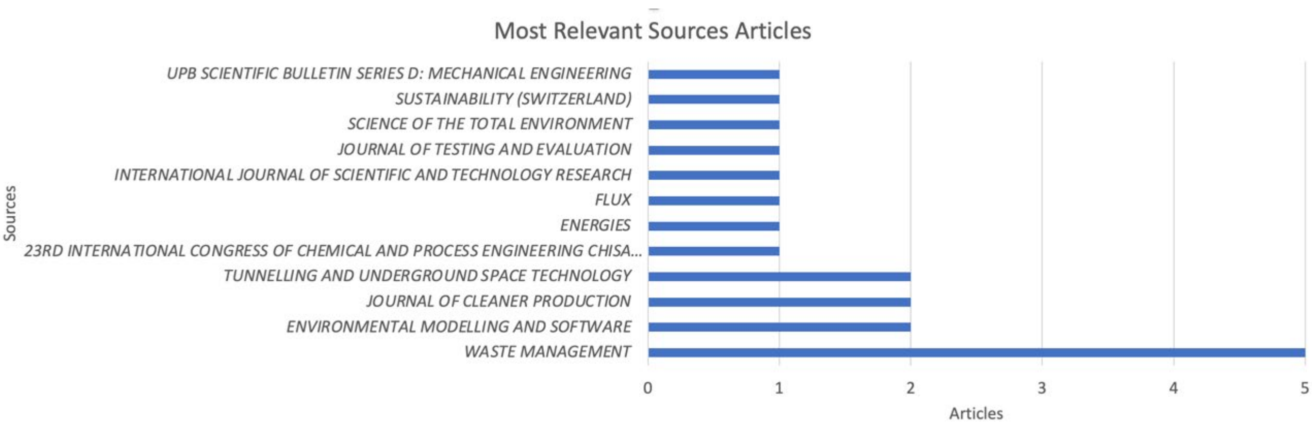

Figure 4. Most relevant sources using R-studio software and bibliometrix library of the automated waste collection system (AWCS) scientific literature found in Scopus.

Figure 5 presents the world's scientific production on the topic. Countries are marked in two colours. Those indicated in grey are where no research was completed related to the topic; blue-marked countries are those where scientific research and publications were carried out. As can be seen, most documents were from Spain and the USA, followed by China, France, India, Italy, the UK, Chile, Greece, and Finland.

Figure 6 shows a word cloud created considering the authors' keywords and their frequency. The keywords with the highest frequency are those represented in a bigger size. A maximum of 50 words were defined in the setting area. Terms such as "life cycle assessment", "greenhouse gases", and "waste collection" should be highlighted.

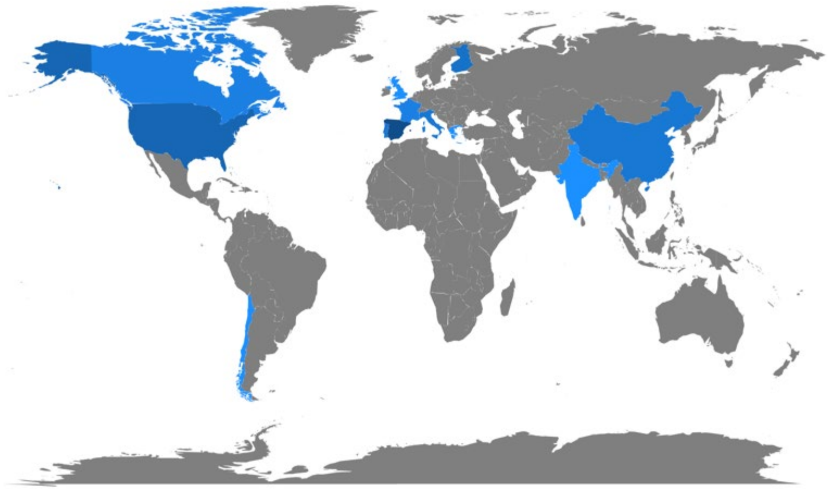

Figure 5. World's scientific production using R-studio software (Version 1.4.1106) and bibliometrix library of the automated waste collection system (AWCS) scientific literature found in Scopus.

Figure 6. Word cloud of the author's keywords extracted from the database analysed using R-studio software and bibliometrix library of the automated waste collection system (AWCS) scientific literature found in Scopus.

Figure 7 shows the relationship between the development degree (density) and the relevance degree (centrality) to discriminate between emerging, niche, motor, and basic themes. The identified emerging topics were "costs" and "greenhouse gases", the motor topics were "cost-benefit analysis" and "environmental impact", and the central topic was "waste management".

Figure 8 shows the thematic evolution in the period of the scientific publications of the database analysed, divided into two periods, 2009–2015 and 2018–2022. The first period was more focused on the topics "environmental impact," "waste collection", "waste management", and "municipal solid waste". In the second period, some concepts changed over the years. For example, "waste collection" evolved into three different concepts in the second period: "waste collection", "waste management", and "greenhouse gases". Something similar happened with the "waste management" keyword, which evolved into "waste management" and "greenhouse gases".

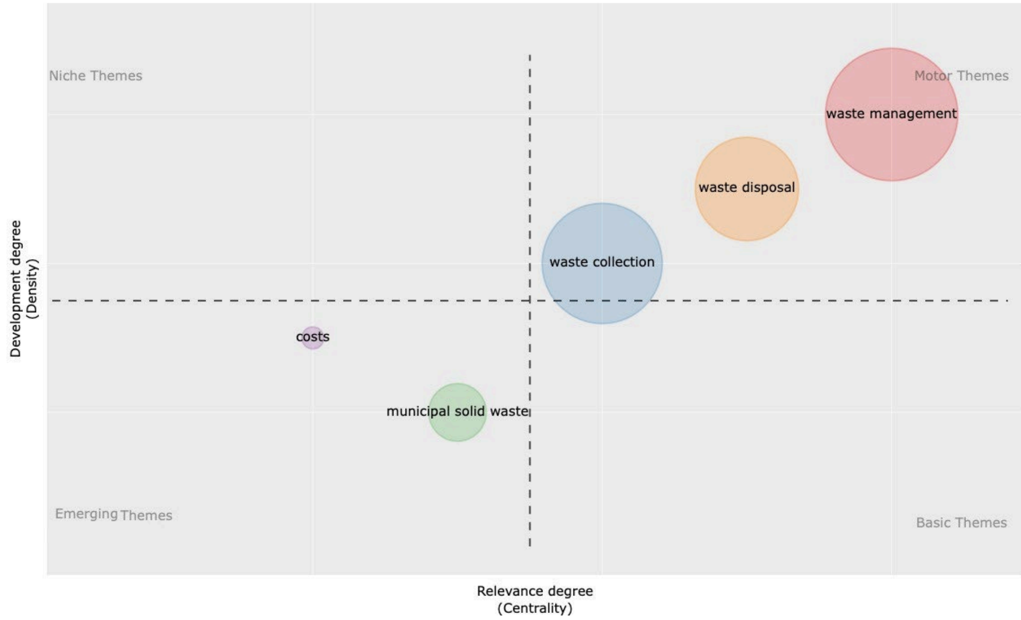

Figure 7. Thematic map during the period 2009–2022 using R-studio software and bibliometrix library.

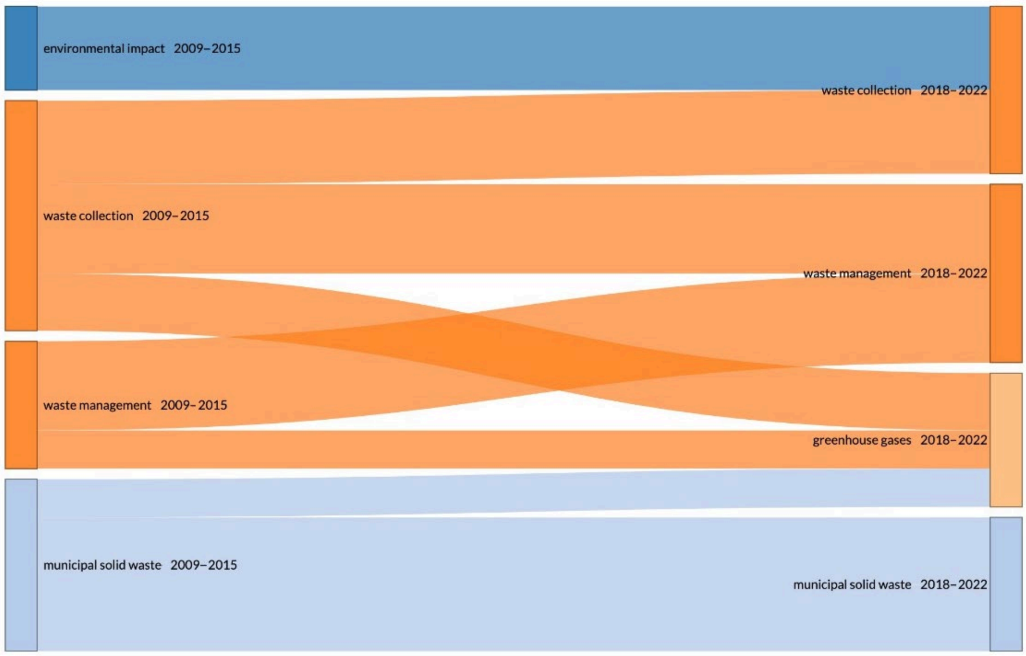

Figure 8. Thematic evolution during the period 2009–2022 using R-studio software and bibliometrix library.

Figure 9 shows the factorial analysis of the database. To achieve this, a multiple correspondence analysis method (MCA) was used on the authors' keywords. The number of terms was set to 25 and the number of clusters was set to auto. The map shows two clusters, a blue one and a red one. The blue cluster includes keywords such as "gas emissions", "waste collection", "waste disposal", and "cost-benefit analysis". The red cluster includes keywords such as "pneumatic control", "greenhouse gases", "waste management", and "life cycle assessment".

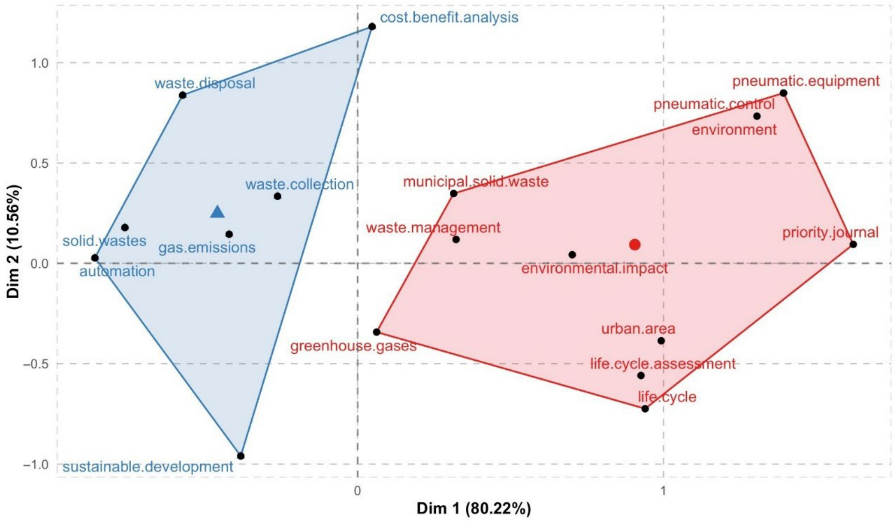

Figure 9. Multiple correspondence analysis method extracted from the database between 2009 and 2022 using R-studio software and bibliometrix library.

3. Advantages and Disadvantages of AWCSs

The advantages of such systems can be found for different stakeholders [22]. For users, the service is available 24 h per day, 365 days per year; inlets for waste deposition are safe, ergonomic, and accessible; there is easy access for users with physical limitations; and there is an improvement in public hygiene conditions. For the city, they allow selective collection at the source since waste can be separated and disposed of in different fractions; they are clean and environmentally friendly, albeit with odour; the city creates an image of responsibility and compromises with the environment; and since waste collection trucks are taken out of the city, the noise disappears, and air pollution due to CO_2 emissions is drastically reduced. For the economy, there is a reduction in waste collection operational costs, there is a reduced number of personnel needed for operation, there are savings in urban cleaning costs, and there are flexible payback options.

When one studies more thoroughly the ecological impact of AWCSs, energy clearly stands out as the biggest contributor to this impact [23]. This does not come as a surprise for a system that, for its operation, relies on creating fast air currents using a large pipe installation for significant periods of time, several times a day, all days of the week, all weeks of the year. Beyond its significant ecological fingerprint, energy is also an expensive resource, becoming the greatest expense when operating such systems, well beyond other running costs such as salaries. As most of these plants are either operated as a public service (i.e., by city corporations) or by companies under contract with such public institutions, a cost reduction can only be achieved via reducing energy bills (reducing personnel operating costs is very difficult for a plant that requires just token personnel to run).

As the hardware that uses all this energy is not very complex (large fans creating air currents), there is not much margin for optimising energy usage on this front. However, for the operations schedule, that is, the schedule determining when and what waste is collected from the network, there is a wide range of options for optimisation. Surprisingly, this aspect of the operation, albeit being the subject of some researchers' attentions [24,25], is not a really well-explored problem, while truck routing for surface waste collection, conversely, has been the subject of more detailed research [26–28], some of which dates way back [29]. On the contrary, as the existence of several patents such as [18,19,30] seems to suggest, that lack of research in the field does not translate to a lack of interest by the industry.

One of the disadvantages of AWCSs is pipeline failures due to the extreme working conditions of such systems. The pipes are in direct contact with the waste transported at high velocities, where the waste may have all types of geometries and dimensions and may contain improper components of the recollected fractions, such as glass and other ceramic materials of high hardness; this causes the attrition of the pipes. Farre et al. [31] studied the origin of pipe failure in two different AWCSs, to understand the failure's primary cause and to help prevent common issues related to attrition. The results showed that 93% of failures were due to abrasive at attrition, mainly in the elbows and connections and in pipefittings. Moreover, the presence of glass in the transported waste was the main cause of attrition.

4. Market Overview

There are a few companies in the market of vacuum waste collection systems [22]. The Swedish company Envac developed the first automated system in the 1960s, and today has more than 1000 systems installed worldwide. The Spanish company Urban Refuse Development (previously part of the company Ros Roca) also has a wide spread of systems, mostly in Southern Europe. MariMatic (Finland) started with vacuum collection of industrial waste, and since 2010 has also been implementing systems in domestic buildings. Logiwaste (Sweden) was founded in 2006 and is specialised in the hospital sector, although they also work in the residential sector. Other companies such as Atreo (TransVac), Stream, Oppent, etc., are also in the market, but with a lower market share.

According to ADEME [22], the costs of investment in stationary vacuum waste collection systems, excluding construction work and preliminary studies or tests, range from EUR 2.3 million to EUR 13.6 million. These costs vary significantly due to the size of the systems considered. The size of one vacuum waste collection system is adjusted according to the connected population, the number of inlets, the length of the network, and the number of waste fractions collected. The number of fractions collected has a big impact on the number of inlets, the cyclones used, and the number of containers. In the projects studied by ADEME, the average cost per meter of pipe was EUR 1000–3000, and the average cost per inlet was EUR 20,000–70,000. The average investment was 2400 EUR/dwelling and 835 EUR/inhabitant.

A study carried out to evaluate the feasibility of AWCSs in Manhattan using existing transportation infrastructure [32,33] stated that direct operating costs for the proposed pneumatic installations, including the container dray from the pneumatic terminal to the transfer station, would be 30% less than those for conventional manual/truck collection in the two cases. However, due to high initial capital costs, the cost of the pneumatic systems would be between 3.3 and 6.6 times higher than for conventional collection.

The business model to be adopted depends a lot on the project and the company installing the vacuum waste collection system. Some contracts include day-to-day supervision of the system and maintenance (excluding the cleaning of the inlets and transporting of containers to the waste disposal sites), whereas others integrate the inlet cleaning and transporting of containers to the treatment sites. These different business models also impact the manpower needed to run the systems, which can vary from 1 FTE to 2.5–3 FTE; therefore, staff costs account for 25% to 80% of the total operating costs. The other important cost of such systems is electricity consumption.

It is also interesting to highlight that the funding mechanisms for vacuum collection systems follow three models. In the first model, mostly used in France and Spain, the systems are owned by the local authorities; in this case, the final user pays the same as in other waste collection systems. In the second model, used in Sweden, the system is usually financed by the owners of the connected buildings, who pay the operating costs with an annual fee proportional to the dwelling surface. Finally, in the third model, used in Nordic countries and the UK, the systems are funded by private investors and the final user pays for it when buying the house; the operational costs may be paid via taxes to the municipality or via direct payment to a private manager.

A summary of some representative systems is presented in Table 1. As can be seen, the first AWCS was built in New York in 1975, but it was not until 2002 that the second one was built in Barcelona and shortly after in Stockholm. The number of systems has been growing steadily since then at a rate of 2–3 systems per year.

Table 1. Representative commercial vacuum waste collection systems. Based on [22] and completed by the authors.

Start-Up Date	Localisation	Application Area	Connected Dwellings	Connected Inhabitants	Supplier Company	Targeted Capacity (Tonnes/day)	Number of Fractions	Types of Waste Collected
1975	Roosevelt Island, New York, USA	Existing area	4300	14,000	Envac	7	1	RHW
2002	Forum, Barcelona, Spain	New district	6200	16,000	Ros Roca	20	2	Food waste, RHW
2004	Hammarby Sjöstad, Stockholm, Sweden	n.a.	2095	n.a.	Sweco	n.a.	3	Paper, organics, RHW *
2005	Buenavista, Portugalete, Spain	Existing area	7600	19,000	Ros Roca	22	2	Packaging, RHW
2007	Sondra Station, Stockholm, Sweden	n.a.	3240	n.a.	n.a.	n.a.	n.a.	n.a.
2008	Wembley Stadium, UK	New district	2300	6400	Envac	23	3	RHW, food waste, packaging
2008	Esperit Sant Hospital, Santa Coloma Gramenet, Spain	New development	n.a.	n.a.	Ros Roca	2–1	3	RHW, metal, plastic, linen
2008	Torrijos Market, Madrid, Spain	New development	18	500	Ros Roca	3	2	RHW, metal, plastic
2009	T1 Barcelona Airport, Spain	New development	n.a.	n.a.	Ros Roca	10	4	RHW, paper, organics, metal, plastic
2011	Rivas, Portugalete, Spain	Existing area	2000	6500	Ros Roca	25	2	Packaging, RHW
2011	Galdakao, Vizcaya, Spain	Existing area	6100	19,500	Envac	25	4	RHW, paper, packaging, food waste
2011	Est Ensemble Romainville, France	Existing area	2300	5300	Envac	12	2	HRW **, RHW
2011	Pamplona, Spain	Existing area	4000	12,500	Ros Roca	12	3	RHW, paper, metal, plastic
2011	Ḥarām Grand Mosque in Mecca, Saudi Arabia	Existing area	n.a.	2 million (visitors/day)	MariMatic	600	1	RHW
2011	King Abdullah Financial District, Riyahd, Saudi Arabia	New area	n.a.	n.a.	Envac	145	2	RHW
2012	Lusail City Marina District, Qatar	New area	21,000	55,000	Envac	60	2	RHW, metal, plastic
2012	22@, Barcelona, Spain	New district	14,000	14,000	Ros Roca	14	2	Food waste, RHW
2012	Helsinki, Finland	Existing area	n.a.	5091	n.a.	5.5	4	RHW, organics, paper, carton

Table 1. *Cont.*

Start-Up Date	Localisation	Application Area	Connected Dwellings	Connected Inhabitants	Supplier Company	Targeted Capacity (Tonnes/day)	Number of Fractions	Types of Waste Collected
2012	Salburua Vitoria, Spain	New district	6200	16,000	Ros Roca	20	2	RHW, metal, plastic
2012	Tianjin Eco-City, China	New area	110,000	350,000	Envac	87	2	RHW, food waste
2012	Alicante Airport, Spain	New development	n.a.	n.a.	Ros Roca	5	4	RHW, paper, organics, metal, plastic
2013	Rambam Medical Center, Haifa, Israel	New area	n.a.	n.a.	TransVac (Atreo)	3	2	RHW, linen
2013	Stockholm Royal Seaport, Sweden	New district	1700	3500	Envac	n.a.	4	RHW, paper, plastic, street bins
2013	Amaroussio, Athenes, Greece	n.a.	n.a.	6500	n.a.	16	2	Recyclables, non-recyclables
2013	Trondheim kommune, Norway	Existing area	8000	2500	Logiwaste	6	2	RHW, paper
2013	Eurosky Tower, Roma, Italy	New development	n.a.	n.a.	Oppent	1	1	Wastepaper
2014	Clichy Batignolles, France	New district	1100	2500	Envac	20	2	HRW, RHW
2014	Vallingby Parkstad, Sweden	New district	1400	3000	MariMatic	n.a.	3	Paper, food waste, RHW
2014	High Line Park, New York, USA	Existing area	n.a.	n.a.	n.a.	10.8	3	Paper, carton, organics, RHW
2014	Second Avenue Subway, New York, USA	Existing area	n.a.	nan	n.a.	19.8	3	Paper, carton, metal, glass, plastic, RHW
2014	Hamad International Airport, Qatar	New area	n.a.	5 millions passengers/year	Envac	40	1	RHW
2017	Tampere, Finland	New area	1100	3500	MariMatic	5	3	RHW, food waste, HRW
2017	Beijing Beitou Tong, China	Mixed area	9000	26,000	Envac	23	2	RHW, food waste
2015	Bergen, Norway	Existing area	4000	8000	Envac	7	4	RHW, paper, cardboard, metal, plastic
2016	Tiller Ost, Norway	Existing area	9000	2500	Logiwaste	10	2	RHW, paper
2016	Saint Ouen, Paris, France	Existing area	6200	18,000	Ros Roca	15	3	RHW, paper, metal, plastic

Table 1. *Cont.*

Start-Up Date	Localisation	Application Area	Connected Dwellings	Connected Inhabitants	Supplier Company	Targeted Capacity (Tonnes/day)	Number of Fractions	Types of Waste Collected
2017	Vitry Sur Siene, Paris, France	Existing area	9100	30,000	Ros Roca	25	2	RHW, metal, plastic
2017	Grow-Smarter Project, Stockholm, Sweden	Existing area	350	450	Envac	0.5	1	RHW
2018	Östermalmshallen food market, Sweden	Existing area	n.a.	n.a.	Logiwaste	2	1	RHW
2019	Maroochydore Sunshine Coast, Australia	New area	5000	12,000	Envac	9	2	RHW, metal, plastic
2019	Skandia Fastigheter, Sundbyberg, Sweden	Existing area	9000	450	Logiwaste	8	2	RHW, food waste
2022	Shaheed Park, Kuwait	New area	n.a.	n.a.	URD	3	1	RHW
2022	Sluisbuurt Neighbourhood, Amsterdam, Netherlands	New area	5500	13,500	MariMatic	15	4	RHW, paper, food waste, metal, glass, plastic
2022	Ramat Hasharon, Tel Aviv, Israel	New development	3650	15,500	URD	14	2	Metal, plastic, food waste

* RHW—Residual household waste, ** HRW—Household recyclable waste (paper, cardboard, and packaging).

5. Environmental Aspects

Iriarte et al. [34] quantified and compared, by means of a life cycle assessment (LCA), the potential environmental impacts of three selective collection systems (i.e., mobile pneumatic, multi-container, and door-to-door) modelled on densely populated urban areas. The results show, with a sensitivity analysis, that the mobile pneumatic system at an inter-city distance of 20 km shows the greatest environmental impacts and the greatest energy demand.

A second LCA study on a hypothetical AWCS, located in Helsinki (Finland) was carried out by Punkkinen et al. [35]. Here, a conventional door-to-door waste collection system was compared with its hypothetical pneumatic alternative, also analysing if the number of waste fractions has an impact on the results. The results show that the AWCS has an overall higher impact due to the electricity consumed, but local CO_2 emissions would decrease in the waste collection areas due to the lower truck traffic.

Aranda Uson et al. [36] carried out a LCA study where an AWCS was compared to a traditional truck collection system in Valdespartera (Zaragoza, Spain). The results show that to achieve the best performance, the AWCS needs to operate at loads close to 100%, otherwise, its impacts are higher than the traditional system.

Laso et al. [37] focused on the organic fraction of waste and carried out a LCA comparing door-to-door collection systems with pneumatic ones, also including the recycling process of such organic waste. The results show that despite the fact electricity production and consumption have a significant influence on the results, the energy savings from the recycling of the organic fraction are higher than the energy requirements.

To evaluate the environmental impact of a real AWCS, Chafer et al. [38] evaluated different waste collection systems (trucks—electric, gas, diesel, diesel–electric, and gas–electric—and stationary pneumatic waste collection) using the LCA methodology. Given the high impact of the electricity used in AWCSs (as in the case above [35]), a sensitivity analysis of five energy sources (Spanish energy mix 2008, hydropower, photovoltaic, wind, and a renewable energy mix) was also carried out. This study was based on the system installed in 22@ (Barcelona, Spain) listed in Table 1. The results show that the energy source has a big impact on the results of the LCA, with variations of up to 80%. The environmental impact of each collection system depends strongly on the source of the energy used and, thus, decision-makers should consider the energy source and the expected evolution of the energy mix when considering the best waste collection systems from an environmental point of view. In a framework with mostly fossil-sourced energy, the truck collection system shows lesser environmental impacts due to its lower electricity use, whereas in a renewable energy environment, the stationary pneumatic waste collection system shows better performance.

Farré et al. [39] evaluated the impact of three different collection systems in an airport following the LCA methodology. The systems considered were a traditional AWCS, an innovative pneumatic AutoWaste compact collection system, and a truck system. The results show that the pneumatic collection system with the innovative AutoWaste compact central unit can reduce the annual flow of greenhouse gases into the atmosphere (kilograms of carbon dioxide equivalent for 30 years and per tonne) by up to 25% compared to a pneumatic collection system with a conventional central unit.

6. Conclusions

This manuscript shows that automated waste collection systems (AWCSs) have a niche in the market, although there is not much published research on the topic. Most published documents are from a few countries around the world (i.e., Spain, the USA, Canada, China, India, Sweden, and Chile). The keywords mostly found in the literature were "life cycle assessment", "greenhouse gases", and "waste collection". The emerging topics were "costs" and "cost-benefit analysis".

The increase in the importance of sustainability and the need to reduce the impact of waste in our cities brings a clear future to this technology. Therefore, the disadvantages of this technology identified should be further researched to improve its deployment. Both economic and environmental studies identified the electricity used in the operation of AWCSs as the main disadvantage; therefore, studies such as those using artificial intelligence to reduce energy consumption are essential. Although there are just a few scientific papers on this topic, several patents provide potential answers to the problem.

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