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IMPROVING WASTE SEPARATION IN PUBLIC SPACES – A FIELD STUDY FROM AUSTRIAN CITIES

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ABSTRACT

Improving waste separation is fundamental to promoting a more sustainable and circular economy. While waste separation in private households is already widely established, it is often neglected in public spaces such as parks or public squares despite high recovery potential (e.g. of single-use packaging from to-go consumption). Hence, particularly with respect to the public sphere, there is a lack of specific knowledge about separation behaviour and separation performance. In order to fill this knowledge gap, field trials were designed and carried out in an interdisciplinary collaboration effort (cooperation of industrial design, social sciences, waste management) to investigate public separation behaviour and resource potential. Additionally, a novel improvement measure was tested in the form of a "recyclables guidance system". The test setups were implemented at four public test locations in two Austrian cities. The results showed that by installing a centralized waste separation station, about 17% of public waste was collected separately and 20% of recyclables were correctly disposed of in the test areas. The implementation of a guidance system resulted in a slight overall improvement in separation performance (total recyclables collection rate +4.6%) and thus shows potential as a cost-effective measure for future applications. The results of this study contribute to a better understanding of waste separation behaviour and have practical implications for promoting more sustainable waste management practices in public spaces.

1. INTRODUCTION

1.1 Waste collection in public spaces

Separate waste collection is fundamental to enabling high-quality material recycling and is one of the key priorities in the EU's circular economy strategy. By progressively increasing the targets for the reuse and recycling of municipal waste, the EU aims to bring about a transformation towards circular material utilisation. Recycling quotes for plastic packaging of 50% by 2025 and 55% by 2030 must be met (directive 94/62/EG, Article 6), and a separate collection target of 90% for beverage packaging must be achieved by 2029 (EU directive 2019/904, Article 9). While in the EU waste separation schemes are widely implemented in private households and some privately managed semi-public spaces, such as public transport stations, airports, and shopping malls, they are often overlooked in public areas like parks, pedestrian zones, and streets, where the primary focus is on preventing littering. A survey among Austrian municipalities in 2024, for example, revealed that only 1% of public waste containers are intended for separate waste collection (Egger, 2024).

Although public waste represents a relatively small waste stream, approx. 2 to 5% of the municipal solid waste in Austria (MSW) (BMK, 2023; Kladnik et al., 2024; TBH, 2021), the few published studies on this waste stream indicate that its resource potential is high. For example, in the city of Krems (Austria), over 50% of the public waste was found to be recyclables (Kladnik et al., 2024) and waste analysis from other regions (Germany, Vietnam, Belgium) have shown similarly high percentages (Gellenbeck and Reuter, 2020; Pham Phu et al., 2019; Verstegen et al., 2022). Especially at urban hot spots, including places in the proximity of eating establishments (high generation of recyclables) or at places with a high pedestrian frequency (high proportion of recyclables), such as shopping streets, the potential for resource recovery is high (Gangl et al., 2022). If correctly disposed of and collected, these materials could be reintroduced into a recycling scheme and contribute to a circular economy. However, waste in public spaces plays a crucial role not only because of the valuable recyclable materials it contains, but also because of its high visibility and its potential to act as a "role model" and driver of social change, encouraging sustainable behaviour by setting a positive example in public.

A practical reason for the current lack of waste separation in public spaces may be the already high operational

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costs associated with public waste management, particularly in the collection process. When roughly compared to household waste collection costs (Province Lower Austria, 2022; Rechnungshof, 2014; Reh et al., 2014), the costs of managing public waste (KPLUSV, 2020; TBH, 2021; Wilts et al., 2022), could be up to seven times higher per tonne. Additional efforts for introducing separation schemes, including costs for container acquisition, extra storage space and waste transport, potentially act as further cost drivers.

Beyond operational factors, the success of collection schemes heavily relies on citizen engagement. Studies from Austria show that separate collection of waste has not yet become a social norm in public spaces and is considered a lower priority compared to households (ARA, 2023; Gök, 2023; Gök et al.; Hartl et al., n.d.), which presents greater challenges for the implementation.

1.2 Factors influencing waste separation behaviour

Effective recycling programmes rely on a well-designed collection infrastructure. Factors such as bin colour, shape and size, which influence visibility and attractiveness, may play an influential role in driving participation. As findings from experimental studies suggest, changing the appearance of waste bins by covering them with pleasant brightly coloured nature designs (Gangl et al., 2022; Lin et al., 2016), using bright green compared to grey bins (Montazeri et al., 2012) or using compost bins with the highest design preference scores (Leeabai et al., 2022) positively enhanced waste separation under certain conditions. However, it is not a general rule that container designs with high consumer preference (e.g. preferred colours and opening shapes or fun design) are able to trigger a positive behavioural response, as shown by Jiang et al. (2019), Leeabai et al. (2021) and Supakata (2018). The effect may also depend on the context and vary from location to location (Gangl et al., 2022). In any case, unclean-looking containers and surroundings can discourage consumers from using containers and should be avoided (Gangl et al., 2022; Hartl & Hofmann, 2024; Supakata, 2018).

In addition, it is important to incorporate design features that clearly communicate recycling information, as knowing the rules of correct waste disposal is essential (Rousta et al., 2017; Uehara et al., 2022). The provision of recycling information directly on containers, for example applied in the form of clear and/or encouraging signs and stickers, showed a positive effect on waste separation in some studies (Austin et al., 1993; Jiang et al., 2019; Rousta et al., 2015; Sussman et al., 2013). Interventions that provided information indirectly, such as through educational lectures or the distribution of information leaflets or displays, have shown mixed results, highlighting the gap between people's intentions and their actual behaviour (Abbasi et al., 2020; Árnadóttir et al., 2019; Moreland & Melsop, 2014; Sadeghi et al., 2020; Tangwanichagapong et al., 2017). Rousta et al. (2017) emphasized that, in addition to information design, the way of conveying information is crucial and that it should be presented recurrently in a way that engages users. The use of recurrent and consistent container and signage design and established colour coding is also highlighted as beneficial in other studies (Ahmed et al., 2016; European Commission et al., 2024; Lee & Manfredi, 2021; Wu et al., 2018).

While studies on improving waste separation use different strategies and reach different conclusions, they generally agree that making separation easy and convenient for consumers is essential. Therefore, the setting conditions - encompassing the distance to waste bins, their arrangement, placement and noticeability - play a predominant role (Andrews et al., 2013; DiGiacomo et al., 2018; Gangl et al., 2022; Kalatzi et al., Leeabai et al., 2019; 2015; McCoy et al., 2018). More convenient setting conditions have shown to be especially effective if coupled with other incentive programs or improvements in information (Miller et al., 2016; Moreland and Melsop, 2014; Rousta et al., 2015; Struk, 2017). Waste bins positioned within shorter distances are more effective in capturing recyclables (González-Torre and Adenso-Díaz, 2005; Rousta et al., 2015). However, there is no universal distance level that individuals are willing to walk for the purposes of recycling, as this depends on the situation and setting conditions. For example, Leebai et al. (2019) suggest thresholds between 8 and 410m in which waste disposal behaviour may be affected, depending substantially on the walking path direction. Concerning the arrangement of the separation containers, studies suggest that it is critical that these be placed side by side, as short distances may already be a barrier to performing waste separation and may increase contaminations and decrease separation efficiencies (Andrews et al., 2013; Jiang et al., 2019; Leeabai et al., 2019).

Overall, findings from experimental studies suggest that the key factors to ensure participation in separate waste collection are: (1) the availability of appropriate recycling infrastructure (bin design), (2) convenience, encompassing setting conditions (e.g. waste bin distance and arrangement), and (3) clear information on waste separation. Considering the regional context in infrastructure design is, in any case, critical since preferences and associations towards container design and waste types vary depending on the region (Jiang et al., 2021; Keramitsoglou and Tsagarakis, 2018; Schloss et al., 2018).

1.3 Objectives of the present study

Although numerous studies have examined waste separation behaviour, particularly in a semi-public context such as universities (Abbasi et al., 2020; Ahmed et al., 2016; Andrews et al., 2013; Austin et al., 1993; Cheung et al., 2018; Jiang et al., 2019, 2021a; Kalatzi et al., 2015; Lee and Manfredi, 2021; Leeabai et al., 2019, 2022; McCoy et al., 2018; Miller et al., 2016; Moreland and Melsop, 2014; Supakata, 2018; Tangwanichagapong et al., 2017), research on recycling in other public spaces remains limited. This context poses unique challenges, such as high collection efforts, a lack of separation infrastructure and separation norms, which need to be addressed for successful implementation.

This research pioneers a systematic examination of waste separation behaviour in public settings through a novel, empirically-based field test design. The study aims to:

1. Assess the impact of introducing waste separation in public spaces on separation performance (collection, capture and contamination) across different waste types, and identify opportunities to optimise resource recovery.
2. Explore whether waste separation can be enhanced by implementing an improvement measure using a "recyclables guidance system" based on wayfinding principles.

As an essential part of the field study, centralized separation stations were introduced in multiple public locations and a novel guidance system for recyclables was developed and tested under real field conditions. The field tests were accompanied by comprehensive waste audits, which are the focus of this paper, as well as behavioural observations, which are part of a separate publication (Hartl et al., n.d.).

2. METHODS

The field tests were developed by an interdisciplinary project team combining the research areas of social science, industrial design and waste management and were carried out in spring/ summer 2023 at four public test locations identified as "waste hotspots" in two Austrian cities. At these locations, first, a central station for waste separation (SS) was installed, followed by the installation of a "recyclables guidance system" on the surrounding residual waste containers (RWC) as a potential measure of improvement. Detailed waste analyses were performed to evaluate the effects of these interventions and their overall impact. The specific elements of the study are detailed below.

2.1 Field tests

The field test setup includes the following steps: 1. Installation/ modification of the central separation station (SS), 2. Stabilisation period I, 3. Baseline waste audit (base), 4. Intervention (guidance system) 5. Stabilisation period II, 6. Post waste audit (post), as shown schematically in Figure 1 and described below. Further details on the test setup and locations can be found in Supplementary Material (SM) (see chapters 1.1 to 1.6).

2.1.1 Test locations and installation of separation stations

As it is known that the level of urbanisation influences participation in separate collection (Edjabou et al., 2014; Feil et al., 2017; Schuch et al., 2023), two cities with different urbanisation levels, Vienna (2 million inhabitants) and Krems an der Donau (50,000 inhabitants), were included. Both cities have similar household waste collection systems in place, which separate paper (packaging and non-packaging), biowaste (bio-waste), glass (packaging glass) and lightweight packaging. In Austria, lightweight packaging collection recently started to be harmonized in January 2023 to include the collection of beverage bottles, composite packaging, metal and all types of plastic packaging (films, trays, cups, etc.) in one collection fraction. In public places of the two cities, mainly residual waste is currently collected, with the exception of public transport areas, where separation bins are often installed. Suitable test locations were selected by identifying public "hot spots" with a high potential for implementing waste separation and a guidance system (high pedestrian traffic, high density of public containers and high consumption in the area). In Vienna, a publicly utilized outdoor area at a university campus (UC) and a frequented forecourt of a subway station entrance (S) were chosen. In Krems, the square in front of the train station (TS) and the pedestrian zone in the old town (PZ) were chosen. At these four locations, a new waste separation station (SS) was introduced (or modified) in addition to several existing public containers for residual waste (RWC). The included RWC containers and catchment areas were defined in such a way that RWCs are located within a reasonable walking radius and along the pedestrian route around the SS to result in comparable container densities at the different locations (between 32 to 41 containers per ha). The number or ratio of SSs to RWCs that were included varied depending on the location conditions, ranging from 1 to 13 to 1 to 6. The approach of introducing one centralized SS instead of a comprehensive replacement of all existing RWCs was chosen to min-

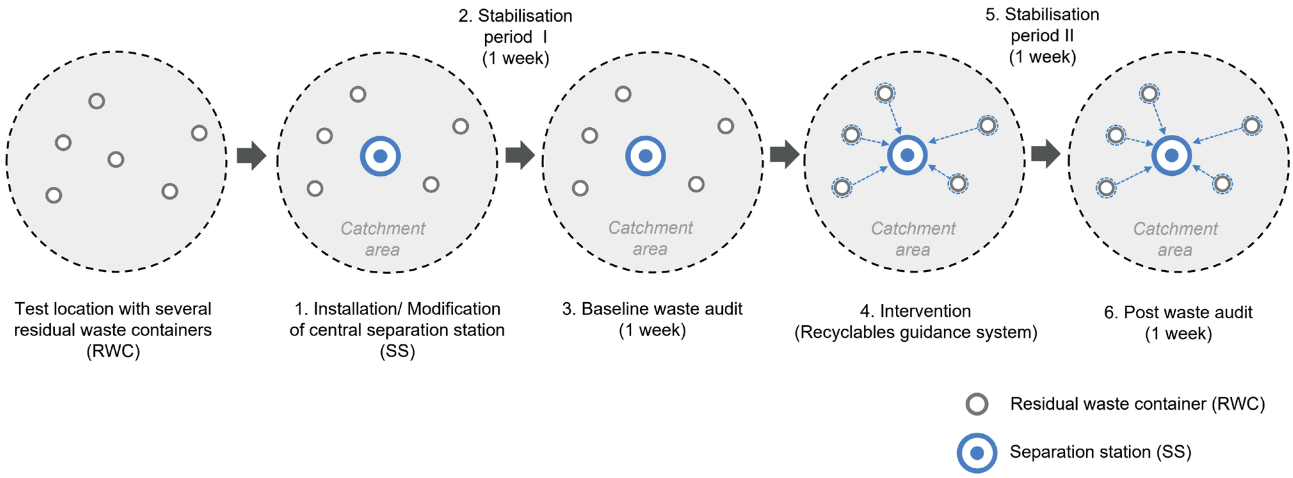


FIGURE 1: Scheme of the field test setup.

imize the additional efforts in disposal logistics and, thus, to present a more realistic implementation scenario. The positioning and design of the SS was done in consultation with the local authorities and as joint effort of the interdisciplinary project team, taking into account the findings on critical factors for separation behaviour (as mentioned in the introduction) and local conditions. A location analysis was carried out beforehand to determine the optimal central and visible positioning of the SS and the number of included surrounding RWCs. The walking distance from an RWC to the SS ranged between 7m and 135m in the locations (total average of 38m). More information on the test locations is provided in the SM (see chapter 1.1).

The SS comprised separation containers (SC) for coloured and white glass (GL), lightweight packaging (LWP), including composite, metal and plastic packaging, and paper (PAP), which were installed next to an existing residual waste container (SSRWC). The SCs used were of the same design as the containers already installed in the area and were clearly labelled with signage stickers using the locally established colour coding (yellow - lightweight packaging, green or white - glass, red - paper, grey or orange - residual waste) and displaying photographs of commonly disposed of waste items (see further details on signage in SM chapter 1.4). A separate collection of biogenic waste was not considered due to the impracticality (vermin, spoilage, emptying). Therefore, biogenic waste in the study is not a target for recoverable waste, but a target for residual waste. At the University Campus (UC), a separate collection for metal, plastic, coloured glass (GLc) and white glass (GLw) was already in place prior to the study. Hence,

FIGURE 2: a) Field test setting at pedestrian zone in Krems. b) Guidance sticker with text (translated): Residual waste, no recyclables please! Waste separation 25 seconds. c) Overhead signs with text (translated): Waste separation, here!

only modifications were necessary to fit the purpose of this study (see further details in SM chapter 1.1.4.).

2.1.2 Stabilisation period

A stabilisation period of at least one week was arranged to mitigate any disruption or adaption effects of the initial implementation of an intervention and to observe whether any unintended consequences occurred. During this time, no waste audit was conducted.

2.1.3 Intervention - Recyclables guidance system

The guidance system was designed in the form of stickers that were applied to RWCS and aimed at propagating waste separation behaviour by generating attention via signal colours (red) and format (Stop sign) and by providing information in the form of clear separation instructions (Figure 2, a) and b)). The instructions are displayed as a verbal prompt ("Residual waste, no recyclables please!"), include illustrations of waste items and are enforced through colour coding (red = wrong, green = correct) and icons (cross = wrong, check mark = correct). The size of the guidance stickers varied between 42x47cm and 31x35cm depending on the location and container size. The illustrations were chosen in photographic style as these are often preferred over icons (Gangl et al., 2022; YaHan, 2020) and were based upon frequent public waste found in prior waste analysis (Kladnik et al., 2024). The guidance stickers further included information on the walking distance as duration (in seconds and minutes) and direction (arrow) to the next separation station. Duration was chosen as people have a tendency to overestimate walking distances, especially when given in metric units of length, making them potentially less willing to walk (Ralph et al., 2020). In addition, clearly visible overhead signs were placed above the separation station to mark the destination (Figure 2 c).

2.1.4 Waste audit

To evaluate the waste separation behaviour, two waste audits per test location were conducted: one audit as a baseline (base) during one week after installation of the central SS and one audit as a post audit (post) during one week after the intervention. The waste from the test locations was collected daily within a consistent time interval of 24 hours. The containers were emptied into bags, labelled (date, fraction, location) and weighted individually. Bags from RWCs were pooled into one sample and bags from the SCs were treated as individual samples. At the UC, white glass and coloured glass, and plastic and metal were later combined in one fraction in the analysis (GL and LWP) to allow comparison with the other test locations.

The samples were sorted by manual picking analysis separately for each location, for each collection fraction (RWC, SSRWC, GL, PAP, LWP) and for each collection day. The sorting catalogue was mainly based on official separation recommendations for consumers as specified and communicated by the Austrian federal ministry as well as by the municipalities of Vienna and Krems (BMNT, 2019; City of Vienna, 2024; Municipal association Krems, 2024). The waste was sorted into 25 subfractions corresponding to the target fraction of collection (Table 1). There are certain problematic waste items which in previous studies have been found to be commonly confusing to consumers for correct disposal, for example napkins, coffee-to-go cups, coated cardboard packaging and composite packaging, while other waste items, such as plastic bottles, tend to be more easily understood (Andrews et al., 2013; Gangl et al., 2022; Hartl and Hofmann, 2024; Jiang et al., 2021; YaHan, 2020). These items were regarded as separate fractions in the sorting catalogue and some were depicted on the separation signage (coffee-to-go cup, hygienic paper). A detailed sorting catalogue with further specifications on classification and examples of sorting fractions is provided in the SM (see chapter 1.6).

The data were recorded as wet packaging weight, including product residues and moisture. After sorting, the mass of the sorted fractions was documented and cross-checked with the initial sample mass to ensure accuracy. The maximum allowed deviation was set at 3%.

2.2 Performance Indicators (SCR, CR, CL)

In the present study, a comprehensive set of performance indicators was used to evaluate waste separation efficiency, quality and recovery potential.

The separate collection rate (SCR) reflects the share of waste collected in a certain waste container and represents a rough measure for participation in separate collection, as waste composition and contamination are not considered. It is a typical indicator used in official reporting and was therefore included for comparisons and is calculated according to Equation 1.

$$SCR = \frac{\textit{weight of waste collected in container A}}{\textit{weight of waste collected in all containers in the test area}}\ x\ 100\ \% \qquad (1)$$

The capture rate (CR) refers to a specific target waste and is defined as the share of waste correctly disposed of in the target container in relation to the total waste of that type generated (Equation 2). It represents a measure for the separation efficiency of a specific waste type.

$$CR = \frac{\textit{weight of correctly disposed of target waste a in target container A}}{\textit{weight of all target waste collected in all containers}}\ x\ 100\ \% \qquad (2)$$

The contamination level (CL) refers to a certain waste container, where it indicates the share of unwanted materials disposed of in the container (Equation 3). It represents a measure for separation quality in the case of separation fractions (GL, PAP, LWP) and a measure for the recovery potential of recyclables in the case of residual waste (con-

TABLE 1: Sorting catalogue for waste audits.

Waste sorting fraction		Subfraction		Abbreviation
1	Residual waste (rw)	1.1	Biogenic waste - unavoidable food waste and organics	ufw
		1.2	Biogenic waste - avoidable food waste - unpackaged	fwu
		1.3	Biogenic waste - avoidable food waste and beverages - packaged (incl. packaging)	fwp
		1.4	Hygienic paper and sanitary articles	hyg
		1.5	Dog feces	dog
		1.6	Other waste	otw
		1.7	Paper non-packaging contaminants	pco
2	Paper, cardboard, corrugated board (PCC) (pap)	2.1	PCC packaging[1]	ppa
		2.2	PCC non-packaging	pnp
3	Lightweight packaging (lwp)	3.1	Plastic beverage bottles	pbb
		3.2	Other plastic packaging	opp
		3.3	Metal beverage packaging	mbp
		3.4	Other metal packaging	omp
		3.5	Composite packaging - beverage carton	cbc
		3.6	Composite packaging - PCC composite packaging and coated PCC packaging	cpa
		3.7	Composite packaging - coated cardboard cups for liquid food and beverages	ccc
		3.8	Composite packaging - plastic-metal composites	cpm
		3.9	Other lightweight packaging	olw
4	Glass packaging (gl)	4.1	Coloured glass packaging	cgl
		4.2	White glass packaging	wgl
5	Other collection points (o)	5.1	Problem waste	prw
		5.2	WEEE, batteries and lamps	wbl
		5.3	Metals non-packaging	mnp
		5.4	Textiles	tex
6	Sorting residue (sr)	6	Sorting residue	sor

Remark: rw and sr are considered non-recyclables; pap, lwp, gl and o are considered recyclables in the context of the field study taminant in RWC = recyclable material other collection points target factions).

$$CL = \frac{weight\ of\ incorrectly\ disposed\ of\ waste\ a\ in\ container\ A}{weight\ of\ all\ waste\ collected\ in\ container\ A^*}\ x\ 100\ \% \quad (3)$$

The CL and CR generally refer to the sum of subfractions classified as target waste or incorrectly disposed of waste, but can also refer to the specific subfractions a_x (e.g., hygienic paper) in a container A (e.g. PAP), hereinafter referred to as the specific contamination level ($CL_{sp}(a_x)$ A) and specific capture rate ($CR_{sp}(a_x)A$).

In the test setup, a change in indicators (e.g. +/- ΔSCR) before and after the intervention was analysed to evaluate the effect of the guidance system.

2.3 Data treatment and statistical methods

The amount of waste generated and waste separation performance varied considerably over the course of the week among the different test locations. To counteract daily and location fluctuations and obtain weighted results, the main results are presented based on the absolute changes in weekly waste amounts cumulated from all four test locations (total). To identify potential statistically significant effects of the intervention, a paired t-test was applied to compare the means of performance indicators during base and post-audit based on individual daily values. For each test location, and in total (cumulated waste from all test locations), daily performance indicators were assessed, resulting in n=7 observations per collection fraction (RWC, SSRWC, LWP, PAP, GL) per audit week. Hence, seven values of the baseline week are compared with seven values of the post-week.

Prior to the significance tests, the gaussian normality of the data was assessed using a Shapiro-Wilk test to determine whether parametric or non-parametric tests are appropriate. As normality was violated in some cases, a non-parametric two-sample permutation t-test was performed in addition to the regular student's t-test using the Software R. and the function "perm.t.test" (package MKinfer). This test generates the sampling distribution from the observed data rather than relying on the assumption of an existing sampling distribution and is suitable for small sample sizes (Christensen & Zabriskie, 2022; Menke & Martinez, 2004). Significance test results are reported in the main article if the rejection of the null hypothesis is true (confidence level 0.95) and in full in the SM (see SM chapter 2.3).

During the waste sorting analyses, it became evident that waste which was not generated in public space but rather originated from households, shops or restaurants (in this study specified as "unauthorized waste") was consistently disposed of into the bins. As this potentially skews the results, outliers were eliminated from the data analysis if possible (see SM chapter 1.7).

3. RESULTS AND DISCUSSION

The following results are based on extensive waste sorting analysis. In the course of the analyses, a total of 1,665 kg of waste was collected for the analysis (base: 795 kg, post: 870 kg). The quantities varied greatly between the different test locations and over the course of the week, which is reflected in high standard deviations of the average daily quantities (see collection quantities in SM chapter 2.1).

3.1 Waste separation in public spaces

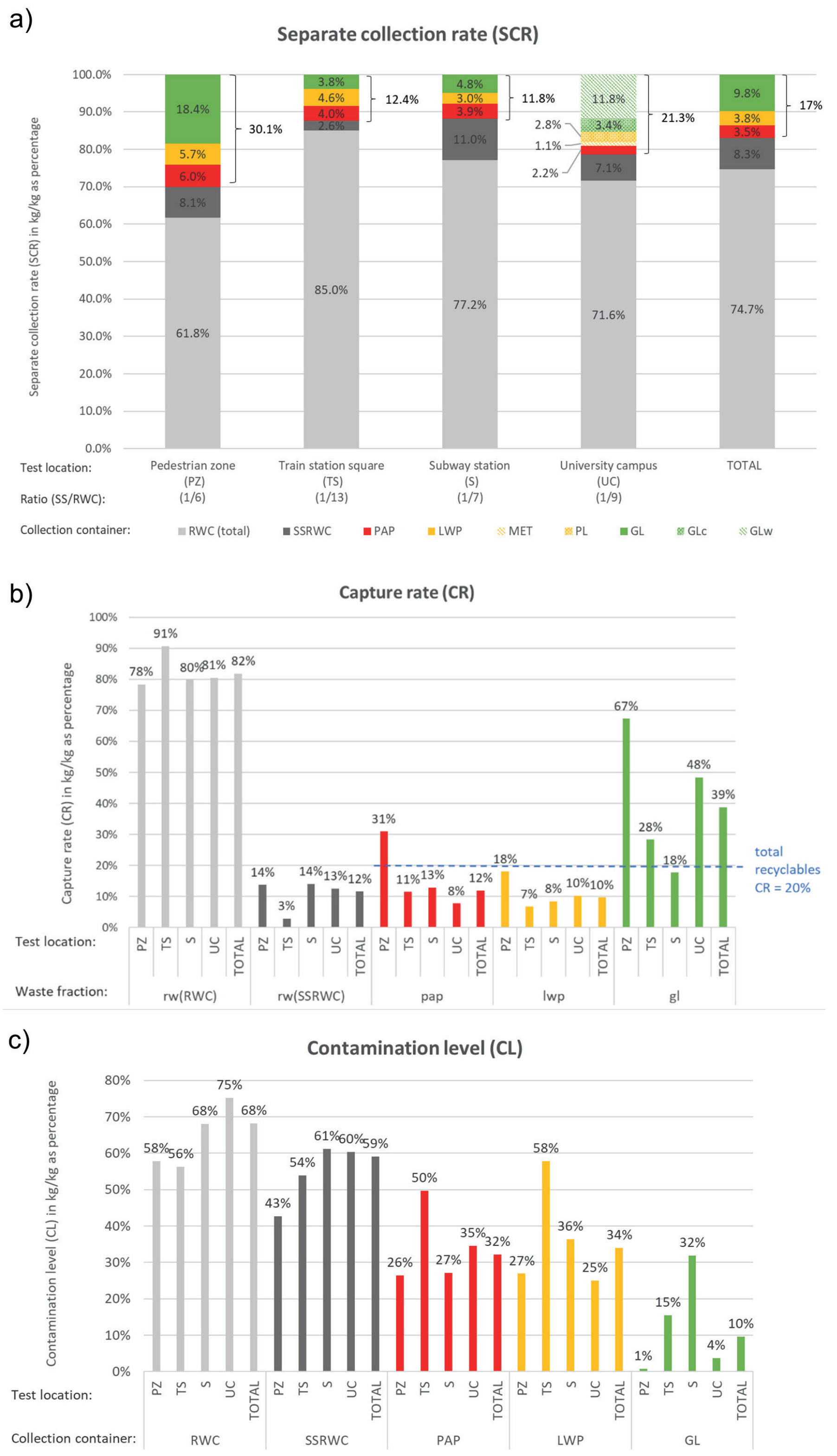
The following results of introducing waste separation are discussed based on the total weekly cumulative waste from all four test locations across both waste audits (baseline + post-intervention week) and are summarized in Figure 3. The overall performance after implementation of the waste separation station is presented independently of the improvement measure (recyclables guidance system), as the impact of the intervention was limited (overall effect < 5%; see chapter 3.2, which details the impact of the guidance system). More detailed results by waste type are presented in Table 2. The results per analysis week, as well as implications of the results on the differences between the test locations, are presented and discussed in the SM (see chapters 2.1-2.6).

3.1.1 Separate collection performance

The separate collection rate (SCR) is determined by the distribution of quantities in the different containers and is, therefore, strongly dependent on the generated waste and the number or ratio of SS/RWC in the test areas. The introduction of separate collection led to total SCR ranging between 30.1% in the pedestrian zone PZ ("best case scenario" with the lowest ratio SS/ RWC 1 to 6) and 11.8% at the subway station entrance S (ratio SS/RWC 1 to 7). Overall, a total SCR of 17% was measured, which was the highest for glass (9.8%) followed by LWP (3.8%) and PAP (3.5%) (Figure 3 a).

3.1.2 Separation efficiency

The separation efficiency (measured by the capture rate CR) indicates which waste types have been better "understood" and are better separated compared to others. In total, the waste separated most efficiently in the public test locations is glass (CR 39%), followed by paper (CR 12%) and lightweight packaging (CR 10%) (Figure 3 b). Specific separation efficiencies (measured by CR_{sp}) for recyclables are presented in Table 2 and more detailed for all waste types and differentiated audit weeks in the SM (see chapter 2.2). Results show that separation commitment varies considerably depending on the specific waste type. Recyclables with higher ranging separation efficiency (CR_{sp} > 10%) include glass packaging (particularly white glass), paper packaging and paper non-packaging (mainly newspapers), plastic beverage bottles and metal beverage packaging, while recyclables with particularly low separation efficiency (< 5%) include paper composite packaging (including coated paper packaging), other lightweight packaging (mainly wooden cutlery), beverage carton and coated cardboard cups (Table 2). These differences may partly be attributed to the fact that certain waste items were depicted on the separation station (e.g. newspapers, beverage bottle; see SM chapter 1.4), acting as an important source of information. Some consumers have been observed comparing their own waste to the separation



Collection fractions: RWC – residual waste, SSRWC – residual waste at separation station, PAP – paper waste, LWP – lightweight packaging (total), MET – metal packaging waste, PL – plastic packaging, GL – glass waste (total), GLw – glass waste white, GLc – glass waste coloured

Waste fractions: rw – residual waste, pap – paper, lwp – lightweight packaging, gl - glass

FIGURE 3: Results of field test based on total amount of waste for each test location and cumulated (total). a) Separate collection rate (SCR), b) Capture rate (CR), c) Contamination level (CL).

TABLE 2: Waste-type specific results on separation efficiency, contaminations and recovery potential based on total amount of waste (base + post) and combined test locations (total).

Collection fraction	Subfraction (a_x)	Indicator
Separation efficiency (CR_{sp})		
		$CR_{sp}(a_x)PAP$
Paper	PCC non-packaging (pnp)	13.8%
	PCC packaging (ppa)	10.0%
		$CR_{sp}(a_x)LWP$
Lightweight packaging	Plastic beverage bottles (pbb)	19.9%
	Metal beverage packaging (mbp)	13.5%
	Composite packaging - plastic-metal composites (cpm)	9.9%
	Other metal packaging (omp) Other plastic packaging (opp)	9.9% 7.9%
	Composite packaging - coated cardboard cups for liquid food and beverages (ccc)	4.1%
	Composite packaging - beverage carton (cbc)	3.7%
	Other lightweight packaging (olw)	2.6%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	1.7%
		$CR_{sp}(a_x)GL$
Glass	White glass packaging (wgl)	48.4%
	Coloured glass packaging (cgl)	26.8%
Contaminations (CL_{sp})		
		$CL_{sp}(a_x)PAP$
Paper top 3	hygienic paper and sanitary articles (hyg)	5.9%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	4.1%
	Paper non-packaging contaminants (pco)	4.0%
		$CL_{sp}(a_x)LWP$
Lightweight packaging top 3	avoidable food waste and beverages - packaged (incl. packaging) (fwp)	13.7%
	PCC packaging (ppa)	4.1%
	hygienic paper and sanitary articles (hyg)	4.1%
		$CL_{sp}(a_x)GL$
Glass top 3	avoidable food waste and beverages - packaged (incl. packaging) (fwp)	2.8%
	metal beverage packaging (mbp)	1.8%
	plastic beverage bottles (pbb)	1.0%
Recovery potential from residual waste		
		$CL_{sp}(a_x)RWC+SSRWC$
Residual waste	**PCC packaging (ppa)**	**10.6%**
	PCC non-packaging (pnp)	**10.3%**
	Avoidable food waste and beverages - packaged (incl. packaging) (fwp)	9.9%
	Coloured glass packaging (cgl)	**8.9%**
	White glass packaging (wgl)	**7.9%**
	Unavoidable food waste and organics (ufw)	7.7%
	Hygienic paper and sanitary articles (hyg)	7.4%
	Other plastic packaging (opp)	**7.0%**
	Metal beverage packaging (mbp)	**5.1%**
	Plastic beverage bottles (pbb)	**4.7%**
	Avoidable food waste - unpackaged (fwu)	4.7%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	**4.2%**
	Composite packaging - coated cardboard cups for liquid food and beverages (ccc)	**3.2%**
	Composite packaging - beverage carton (cbc)	**1.5%**

** Recyclables marked in bold*

signs in accompanying observation studies (Hartl et al., n.d.). However, the differences in the specific separation efficiencies of waste types are expected to be influenced by other factors as well, such as the fact that certain materials are easier to identify or perceived as having a higher value, for example glass (Langley et al., 2011). In addition, separation norms for certain waste materials may be better established as a result of previous sustained awareness campaigns. For composites and coated paper, official separation recommendations are often ambiguous, and for some materials, such as other plastic packaging (e.g. foils, trays and cups), separate collection has only recently been introduced in Vienna and Krems as part of the national harmonisation of the LWP collection (in January 2023) (VVO - BGBl. II No. 184/2014). The findings are consistent with other studies which found particular composites and cardboard cups among frequently misunderstood waste items (Andrews et al., 2013; Gangl et al., 2022; Hartl & Hofmann, 2024; YaHan, 2020).

Compared to separation performance in households, in particular, a higher efficiency for paper separation would have been expected in the present study (CR 12%) as paper is typically separated with rather high efficiency compared to other waste (separation efficiencies in Viennese households: Paper total: 62%, Glass total: 56%, LWP plastic bottle collection: 23%) (MA48 & Huber, 2024).

3.1.3 Separation quality

High levels of contamination in the collection streams can cause problems and increase the costs of further processing and sorting, and should be kept to a minimum (Neubauer et al., 2021). The contamination levels (CL) found in this study are presented in Figure 3 c) and the specific contamination levels for different waste types in Table 2. Waste composition results per container are presented in Figure 4 and in more detail (individual subfractions and audit weeks) in the SM (see chapter 2.5). Highest contamination levels were found in LWP (CL 33.9%), closely followed by PAP (CL 32.2%) and lastly GL (9.6%). Compared to the contamination levels found in household waste, the public CL are generally higher, but most strikingly in PAP (contamination levels reported in households: CL PAP: 3.6% in Vienna; CL LWP: 20-30% in Austria, 21% in Graz; CL GL: 0.4-2.3% in Austria, 0.3-0.7% in Vienna excl. glass colouring contaminations) (Lingitz, 2021; MA48 & Huber, 2024; TBH, 2014). The largest specific contaminations in PAP are hygienic paper and sanitary articles, paper composite packaging and non-packaging paper contaminants (e.g. receipts), all of which are fibre-based. The largest sources of contamination in LWP are packaged food waste, paper packaging and hygienic paper. The highest contaminations found in glass were due to packaged food waste, metal beverage packaging and beverage plastic bottles (Table2). Waste composition and contaminations reflect common types of waste from public activities, including shopping and to-go consumption. This includes items such as coated paper packaging, food waste, napkins, drink bottles and receipts.

3.1.4 Recovery and optimisation potential

To interpret the impact of the field test, it is important to consider results in relation to the available potential of recyclable materials. To illustrate the overall results of waste separation in the prescribed test setups, the total quantities of waste collected and analysed at the four test sites are summarised in Figure 5 by means of material flows.

Looking at the total generated public waste (regardless of collection container), there is a material recovery potential (percentage of all recyclables) of about 69%, with 59% consisting of packaging. With the introduction of a centralized separation station, located on average 38m walking distance in the test areas, a total of 20% of these recyclables were correctly separated, while the remaining 80% were either disposed of in the residual waste (78%) or in an "incorrect" separation fraction (2%) (see total recyclables capture rate CR in Figure 3 b) and waste flows in Figure 5). Despite the presence of a separation station, between 59% of the collected residual waste in SSRWC and 68% in RWCs was recyclable material (see contamination level CL Figure 3 c) and waste composition in Figure 4). In total (RWC + SSRWC), recyclables constitute around 65% of residual waste, while the greatest recovery potential from residual waste lies with paper (packaging and non-packaging 20.9%), glass packaging (white and coloured 16.8%), other plastic packaging (7.0%), metal beverage cans (5.1%) and plastic bottles (4.7%) (see Table 2 for details). The share of recyclables in the public residual waste was, in any case, higher than in households, where about 21% to 31% can be expected (if biogenic waste and other collection points target factions are not considered) (Beigl, 2020; MA48 & Huber, 2024) and compared to previous studies, where about 52% was measured in public waste (Kladnik et al., 2024). This may be due to the fact that hotspot locations were analysed.

To reduce the total amount of residual waste, efforts to optimise waste separation should focus on those wastes that are currently separated with low efficiency (indicated by low CR), while simultaneously showing a high recovery potential in terms of mass (indicated by high CL in residual waste). This applies in particular to other plastic packaging (incl. film, trays, cups, etc.), constituting almost 7% of residual waste, with only 7.9% being correctly disposed of (see Table 2). With the introduction of a deposit return system in Austria in 2025 (AWG 2002, BGBl. I Nr. 102/2002), this waste category will become particularly important as the new main collection target (plastic bottles and metal cans will no longer be targeted in LWP). Similarly, paper composite packaging (ccc, cbc, cpa) make up 8.9% (in sum) of total residual waste, but only 1.7% (cpa) to 4.1% (ccc) are correctly disposed of. Paper packaging and non-packaging, which each account for more than 10% of residual waste, show significant potential for improvement as it is typically much better separated in households in relation to other waste fractions (see also chapter 3.1.2).

Overall, the results suggest that clear container labelling and the provision of adequate separation infrastructure alone may not lead to sufficient separation quality and efficiency in busy public spaces, where waste separation

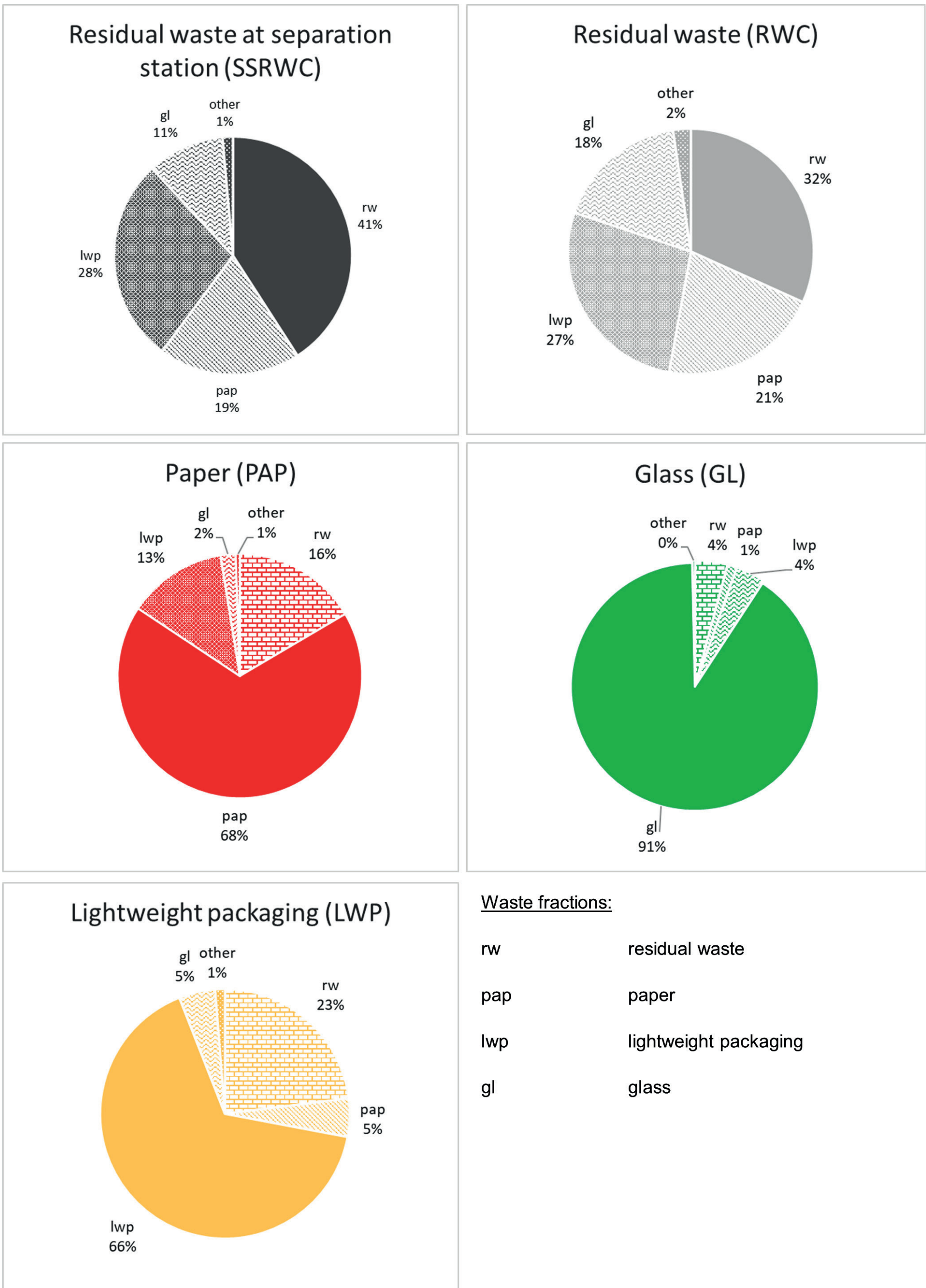


FIGURE 4: Composition of public waste (excluding sorting residues) per collection container based on the total amount of waste cumulated from all test locations (total).

is not yet perceived as a social norm (Gök et al.; Hartl and Hofmann, 2024). Communicating the purpose of separate collection and the material transformation behind recycling (Hartl and Hofmann, 2024; Winterich et al., 2019), as well as broader awareness campaigns or age-targeted initiatives that integrate digital tools (Concari, 2023), could be further measures to promote waste separation.

While the results highlight the high recovery potential of public waste, the extent to which separated fractions can be effectively utilized or marketed depends on regional recycling infrastructure and market demand. Austria has a well-established recycling system for glass, metal and paper. However, lightweight packaging, especially composite and mixed plastic fractions, often face significant challenges due to contamination, as well as fluctuating demand and marketability (ARA, 2022; Neubauer et al., 2021). The effectiveness of separate collection in public spaces, therefore, relies not only on improving consumer behaviour but also on ensuring viable processing and end markets for recyclables.

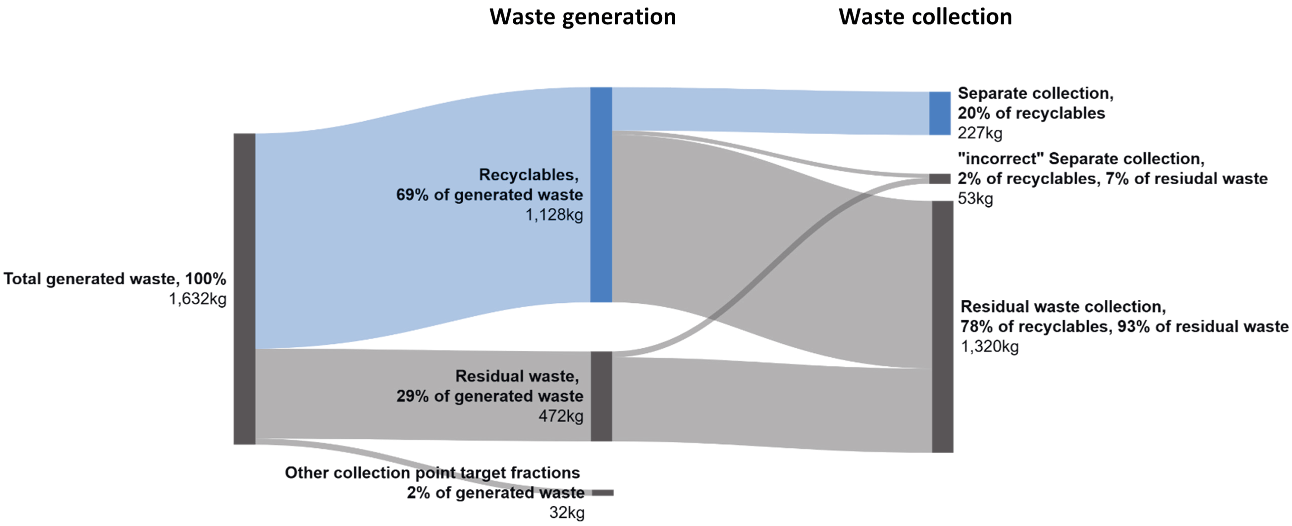


FIGURE 5: Waste material flows illustrating recovery potential and overall separation performance in the test areas, based on total analysed waste (excl. sorting residues). Values were rounded for illustrative purposes.

3.2 Effects of the guidance system

The effects of the guidance intervention are discussed based on the absolute differences in weekly performance indicators before and after the intervention for total waste (cumulated from all test locations). In addition, results were tested for significance based on the mean difference in daily performance indicator values (n=7) between the two audit weeks. Significant test results (p-value < 0.05) are reported below and detailed results are reported in the SM (see chapter 2.3).

In total, the intervention showed a positive effect on the separation of glass, as more waste was collected in the glass container (change in separate collection rate ΔSCR + 1.93%, result significant based on mean difference: +2.17%, p-value = 0.0469), glass waste was properly separated to a greater extent (change in capture rate ΔCR +9.03%), and it was less contaminated (change in contamination level ΔCL −4.38%). The effect was also positive on lightweight packaging, as more waste was collected in the LWP (ΔSCR + 2.11%), lwp waste was properly separated to a greater extent (ΔCR +4.98%, result significant based on mean difference: +4.65%, perm. p-value = 0.0234) and it was less contaminated (ΔCL −1.10%). Residual waste collection was influenced positively in the SSRWC as the separation efficiency and quality improved (ΔSCR −0.17%, ΔCR +2.36%, result significant based on mean difference: +2.44%; perm. p-value = 0.01562, ΔCL −6.91%). However, a negative effect was observed for paper waste, as less waste was collected in PAP (ΔSCR −0.11%), less paper waste was properly separated (ΔCR −1.02%) and the container was more heavily contaminated (ΔCL +5.74%) after the intervention. Overall, however, there was an improvement in the separation efficiency of total recyclables ("total recyclables capture rate" ΔCR +4.56%, result significant based on mean difference: +4.76%, perm. p-value = 0.03125). The fact that the overall effect was modest (< 5%) is supported by observations in which, in general, few interactions with the guidance stickers were observed (Hartl et al., n.d.). A detailed examination of the specific effects associated with individual waste fractions, which is provided in the SM (see chapter 2.4), allows more nuanced conclusions to be drawn regarding waste-specific behaviour and the design of guidance signage. For example, the negative separation effect for paper waste was due to more non-packaging paper (e.g., newspapers) being disposed of as residual waste after the intervention. This effect may be related to the use of red-coloured guidance stickers (Figure 2 b), which are associated with waste paper in Austria and may have caused confusion. Using attention-grabbing colours with neutral waste associations instead (e.g., pink in Austria) or minimal accents (e.g., a red exclamation mark) could prevent unwanted triggering of specific waste associations.

3.3 Limitations

Waste amounts typically vary significantly throughout the week (Edjabou et al., 2015; Leeabai et al., 2021), as was the case in this study. To avoid variations and evaluate long-term impacts, longer test periods and using average weekly data would be beneficial. The analysis period was limited due to resource constraints and to minimise possible seasonal variations, which should be taken into account when interpreting the results. In general, waste sorting analyses on wet waste, as performed in this study, can give a distorted picture of separation behaviour, as it does not analyse the number and quality of individual "tosses" and is affected by humidity fluctuations among waste fractions. Uncertainties also exist in relation to different moisture contents of different collection fractions, e.g. a typically higher moisture content of paper in residual waste compared to paper in the waste paper container. Waste audits further revealed that in some test locations, owners of local shops and snack bars used public bins to dispose of larger quantities of their commercial waste (unauthorized waste), potentially skewing the results.

Several factors, including the bin design, setting conditions (distance, placement, arrangement of waste bins), and external influences such as weather, the level of greening, car traffic, pedestrian traffic, clientele (e.g., socio-demographic differences), consumption and stay patterns are likely to influence waste disposal and separation behaviour. For example, in busy public places with short stay durations, diffuse pedestrian flows, or cold and rainy weather conditions, attention to waste disposal and separation may be reduced. Conversely, low vehicle traffic, favourable weather and ample resting areas could create a calmer environment, potentially increasing awareness and improving waste separation at the site. This study recorded weather and setting conditions, which are mentioned in terms of differences between the test locations in SM Chapter 2.6, and provides a qualitative description of the test locations in SM chapter 1.1. Beyond that, external factors were not systematically recorded, which is a potential limitation to the comparability of the study results.

4. CONCLUSIONS

In order to gain insight into the public's waste separation behaviour and to test the effectiveness of a guidance system for recyclables, field tests were conducted in public places in Austrian cities. The results of comprehensive waste audits show that the resource potential at public waste hotspots is high (69% recyclables, 59% packaging), making these areas well-suited for the introduction of waste separation. The introduction of central separation containers has resulted in 17% of the waste in the catchment area of the test locations being collected separately and 20% of the recyclables being captured for recycling. Although these results would fall short of the ambitious collection and recycling targets (e.g. 80% collection target for plastic packaging according to ARA (2022)), they represent a substantial improvement over the current situation where public waste separation is currently very limited in Austria (Egger, 2024;) and other European Countries (European Commission, 2021). In terms of collection quality, the results showed the highest contamination levels in lightweight packaging (CL 33.9%), closely followed by paper (CL 32.2%) and glass waste (9.6%), which exceed the contamination rates in Austrian households.

Beyond the specific focus on the public context, the results also provide valuable insights into waste separation behaviour across different waste types. It appears that some waste types are already much better understood and separated than others. To improve resource recovery, the separation of already "well-understood" waste types, such as plastic and glass bottles, should be continuously promoted. However, specific optimisation potential exists for improving the separation of other plastic packaging (cups, trays, films), paper composite packaging (including coated paper and cardboard) and paper in general (packaging and non-packaging) as these are not yet well separated. To reduce contaminations, measures specifically targeting the identified problematic contaminants such as hygienic paper and packaged food waste (e.g. additional instructions "please no used tissues or food leftovers") could be effective.

The pilot introduction of a recyclables guidance system, which was tested as a low-cost improvement measure to increase waste separation in the test areas, showed an overall positive effect. The collection of total recyclables increased by about 4.6%. However, the results are more differentiated for different types of waste and further research on wayfinding interventions is recommended to substantiate the results, as also accompanying behavioural studies did not provide clear evidence of consumer interaction with the guidance signage (Hartl et al., n.d.). While the results provide an overall picture of public hot spot areas, the location conditions and results varied greatly in individual situations. Future studies could include the assessment and analysis of external factors such as clientele, landscaping, pedestrian traffic, and length of stay to better understand their impact on separation behaviour and improve study comparability.

Although the implementation of waste separation in public spaces is challenging, it can contribute to waste reduction and establish waste separation as a societal standard. This study provides valuable insights into waste separation behaviour and has important implications for the design and implementation of waste separation schemes.

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