Measuring spatial access to recovery networks for WEEE: the Bavarian case

Kaan Senoglu, Lukas Messmann

Angaben zur Veröffentlichung / Publication details:

Senoglu, Kaan, and Lukas Messmann. 2026. "Measuring spatial access to recovery networks for WEEE: the Bavarian case." *Cleaner Waste Systems* 14: 100515.
https://doi.org/10.1016/j.clwas.2026.100515.

Cleaner Waste Systems 14 (2026) 100515

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Measuring spatial access to recovery networks for WEEE: The Bavarian case

Kaan Senoglu [a], Lukas Messmann [a,b,c,*]

[a] Resource Lab, University of Augsburg, Universitaetsstr. 12a, Augsburg 86159, Germany
[b] Chair for Production & Supply Chain Management, University of Augsburg, Universitaetsstr. 16, Augsburg 86159, Germany
[c] Green Office, University of Augsburg, Universitaetsstr. 2, Augsburg 86159, Germany

ARTICLE INFO

Dataset link: Measuring Spatial Access to Recovery Networks for WEEE: The Bavarian Case

Keywords:
E-waste
Waste management
Collection centre
Circular economy
Spatial autocorrelation
Moran's I

ABSTRACT

Effective management of Waste Electrical and Electronic Equipment (WEEE) is essential for advancing environmental sustainability and achieving the EU's circular economy objectives. However, like other EU member states, Germany faces significant challenges in meeting the recycling targets set by EU legislation. Crucially, WEEE collection performance depends on a variety of factors, including an effectively designed collection infrastructure and, presumably, the geographical proximity of dedicated collection facilities. To evaluate the importance of this latter factor, this study applies the approach developed by an Italian study on WEEE collection to the German federal state of Bavaria. In detail, the study at hand quantifies spatial *accessibility* and *availability indicators* for collection centres and correlations between these indicators and collection rates. This serves to answer (1) whether accessibility and availability of collection centres correlate with collection rates, (2) whether spatial discrepancies or clusters in indicators and collection rates exist in Bavaria, and (3) whether the conclusions drawn for Italy can also be drawn for the case at hand. The results hint at differences in municipal waste management structures, particularly in northern Bavaria. However, contrary to expectations and the Italian case, the findings indicate that neither spatial accessibility nor availability significantly influences collection performances. This suggests that policymakers should focus on alternative strategies to enhance WEEE collection rates in Germany (e.g., public awareness, education, or monetary incentives), and, in line with similar recent literature, hints at opportunities to improve the efficiency of the e-waste collection landscape.

1. Introduction

Rapid technological advancements, shorter product lifecycles, and the resulting rise in volumes of Waste Electrical and Electronic Equipment (WEEE or e-waste) have been a growing concern for decades (Andeobu et al., 2021; Shahabuddin et al., 2023). This concern stems not only from the environmental risks associated with poor WEEE management but also from the environmental impacts of primary raw materials production and the squandered environmental and economic potentials when WEEE is not properly recycled or reused (Boldoczki et al., 2021; Messmann et al., 2019). Andrade et al. (2019) report a significant increase in publications on e-waste, indicating growing recognition of this problem. Further emphasising the urgency of the matter, the Global E-Waste Monitor 2024 (Baldé et al., 2024) reports a record 62 million tonnes of e-waste generated in 2022, representing an 82% increase from 2010. The report projects an annual rise of 2.6 million tonnes, estimating e-waste generation to reach 82 million tonnes by 2030. This growth positions WEEE as the world's fastest-growing domestic waste stream, surpassing formal collection and recycling efforts nearly fivefold.

Acknowledging the gravity of the situation, the European Union has made efforts to address the issue. The Directive, 2002/96/EC (2002) was introduced to standardise regulations across member states and promote responsible waste management and recycling practices. Subsequent updates to the directive have aimed to bolster the collection, treatment, and recycling of electrical and electronic equipment, fostering resource efficiency and facilitating the transition to a circular economy. The latest amendment to this legislation, Directive (EU) 2024/884 (2024), underscores the EU's ongoing commitment to tackling the evolving challenges posed by WEEE.

As the largest economy in Europe, Germany has emerged as a significant contributor to WEEE generation, with its e-waste surpassing 1 million tonnes in 2021 (Eurostat, 2024). In aligning with EU directives, the country has incorporated the principles outlined in the WEEE Directive into its national legislation by enacting the Electrical and Electronic Equipment Act (2015/2022). In the German approach,

* Corresponding author at: Resource Lab, University of Augsburg, Universitaetsstr. 12a, Augsburg 86159, Germany.
E-mail addresses: lukas.messmann@uni-a.de, lukas.messmann@gmail.com (L. Messmann).

https://doi.org/10.1016/j.clwas.2026.100515
Received 6 December 2025; Received in revised form 30 March 2026; Accepted 8 April 2026
Available online 12 April 2026

responsibility for WEEE disposal is shared between public-sector recycling entities and manufacturers, with specific roles for retailers and opportunities for voluntary programs (Walther et al., 2010). Despite these efforts, Germany fell short of the EU's mandated minimum recovery rate of 65%, achieving a recycling rate of merely 38.6% in 2021 (Eurostat, 2024). This underscores the need for a critical reassessment of existing strategies and for exploring innovative approaches.

One such strategy is enhancing spatial access to recovery networks. The concept of spatial theory posits that the spatial distribution of collection points significantly impacts the effectiveness of e-waste management systems (Bruno et al., 2021). The underlying premise, supported by evidence from several case studies (cf. Ghisellini et al., 2023; Laeequddin et al., 2022; Shevchenko et al., 2019; Thukral et al., 2023), is that convenience, often operationalised by spatial accessibility, is a sizable factor influencing consumer behaviour in waste disposal. For example, Zhang et al. (2016) highlight the relationship between travel distance and visitation frequency, showing a 25% increase in recycling rates when collection facilities are more accessible. Similarly, Favot and Grassetti (2017) show that the number of collection points correlates positively with the collection rate, although acknowledging differences between densely populated urban and rural regions. However, other research suggests that once a certain 'baseline' of infrastructure is met, other factors may become dominant, such as socio-economic variables like education, income, gender, and age (e.g., Favot and Grassetti, 2017; Thukral et al., 2023), psychological factors like environmental attitude and social norms (Laeequddin et al., 2022; Papaoikonomou et al., 2020), as well as incentives, educational interventions, and awareness building (Ghisellini et al., 2023; Iyer and Kashyap, 2007; Thukral et al., 2023).

Furthermore, the nature of the WEEE waste stream may also be a contributing factor, and most of the mentioned studies do not specifically address e-waste disposal behaviour. While consumers tend to keep old devices rather than dispose of them properly (Laeequddin et al., 2022), materials such as paper and glass are more prevalent and less likely to be stored at home due to space constraints, perceived low value, and limited reuse or resale potential (Chi et al., 2014).

Lastly, regional and national differences in infrastructure and waste management systems warrant differentiated analyses when transferring conclusions from one specific case to another. For example, Ibanescu et al. (2018) compare WEEE collection rates and recycling rates across five EU countries, and Gonda et al. (2019) find that regional recycling rates can deviate from the national average by up to 40% due to local conditions. The regional disparities between northern and southern Italy in WEEE infrastructure and collection rates reported by Ghisellini et al. (2023) align with this observation. Studies in Italy, Belgium, and England (Favot and Grassetti, 2017; Gonda et al., 2019; Zaharudin et al., 2021) underscore the significance of regional differences in e-waste disposal behaviour.

To provide context to these discussions, we use the study by Bruno et al. (2021) as a methodological foundation (see Section 2) for quantifying the influence of convenience in terms of spatial accessibility and availability, and apply it to a structurally different case. The German federal state of Bavaria has the largest number of public-sector collection centres[1] (CCs) in Germany, boasting 1530 facilities (Bavarian Environment Agency, 2022) as of 2021. Its extensive infrastructure renders Bavaria a prime candidate for an in-depth investigation of the spatial accessibility and availability of its collection centres, for contributing to the scientific discussion on factors influencing recycling behaviour, and for evaluating the transferability of the conclusions drawn by Bruno et al. (2021) regarding Italy to the case of Bavaria. Their Italian case study indicates a measurable positive correlation between the proximity of recycling facilities and individuals' inclination towards proper waste disposal practices. This correlation is particularly noticeable when comparing the wealthier regions of northern Italy with the economically disadvantaged southern regions, emphasising the importance of convenient waste management options and highlighting discrepancies in the collection infrastructure.

In summary, access to recycling centres is considered an influential variable in waste disposal decision-making. Literature underscores the multifaceted nature of recycling behaviour, but proximity to recycling facilities stands out as a consistently adduced factor influencing disposal habits. On this basis, a positive correlation between the spatial accessibility and availability of collection centres (CCs) in Bavaria, on the one hand, and collection rates on the other would be anticipated, thereby confirming the conclusions drawn for Italy (Bruno et al., 2021). However, WEEE's characteristics compared to regular household waste as well as regional infrastructural differences warrant challenging the premise of a universal primacy of convenience and spatial accessibility. Employing Geographic Information System (GIS)-based data compilation and statistical analyses, we pursue the following research objectives:

(1) quantifying the **accessibility and availability** of Bavarian collection centres, based on the approach of Bruno et al. (2021), (2) discerning the potential influence of accessibility and availability on **collection rates**, (3) assessing the presence of spatial autocorrelation to determine whether areas with similar WEEE collection performance on the one hand and availability and accessibility indicators on the other hand tend to **cluster together or are dispersed** to provide additional insights into the waste management infrastructure, and (4) discussing whether the results achieved and **conclusions drawn by** Bruno et al. (2021) for the Italian case can be transferred to the case of Bavaria, allowing for specifically Bavarian conclusions and a discussion on the applicability of the methodology in general.

This study contributes to the field in two ways. First, it assesses the transferability and robustness of established spatial accessibility methodologies (specifically Bruno et al., 2021) by applying them to a different, structurally distinct geographical context, providing context for the findings. Second, the study challenges and nuances the premise of a linear positive relationship between facility proximity and collection performance (e.g., Zhang et al., 2016). In detail, we provide empirical evidence that in Bavaria, a region with high baseline infrastructure density, spatial convenience ceases to be the primary predictor of collection rates, suggesting a saturation point at which other factors (e.g., socio-economic incentives) become dominant.

2. Materials and methods

This section describes the methods chosen and the materials used, detailing five accessibility and availability indicators, the specifics of the Bavarian case and the statistical methods employed.

2.1. Spatial access analysis

In the case study at hand, we employ the methodological framework proposed by Bruno et al. (2021), who examine users' spatial access to WEEE recovery infrastructure in Italy. At the core of their approach lies the concept of spatial access, initially introduced by Penchansky and Thomas (1981) in the context of healthcare services. Bruno et al. (2021) introduce two sets of indicators – accessibility and availability indicators – to evaluate the adequacy of service supply and the proximity between users and collection facilities (Table 1).

Spatial accessibility, crucial for users' willingness to use collection facilities, hinges on the relative ease of reaching them from a user's location. Bruno et al. (2021) introduce three **accessibility indicators**:

(a) The *Average accessibility distance* represents the expected average

[1] In this study, the term 'collection centre' (German *Wertstoffhof*) or 'CC' is used analogously to Bruno et al. (2021). It refers to sites operated by public waste management authorities for the collection and temporary deposition of bulky wastes as well as potentially recyclable and/or hazardous materials. This concept is sometimes also referred to as transfer station, civic amenity site, or recycling centre.

Table 1
Accessibility and availability indicators (for one district), according to Bruno et al. (2021).

	Indicator	Formula
Accessibility	*a) Avg. accessibility distance*	$\frac{\sum_{(i\in I)} p_i d_i^{\min}}{\sum_{(i\in I)} p_i}$
	b) Max. accessibility distance	$\max_{j\in J}\left\{d_i^{\min}\right\}$
	c) Cumulative distribution of accessibility distances	$\frac{\sum_{(i\in I \mid d_i^{\min}\le d)} p_i}{\sum_{(i\in I)} p_i}$
Availability	*d) Served population*	$\frac{\sum_{(m\in M:\lvert J_m\rvert\ge 1)}\sum_{(i\in I_m)} p_i}{\sum_{(i\in I)} p_i}$
	e) Provider-to-population ratio	$\frac{\lvert J\rvert}{\sum_{(i\in I)} p_i}\times 100.000$

with $d_i^{\min} = \min_{j\in J}\left\{d_{ij}\right\}, \forall i \in I$

distance users must travel to reach the closest collection facility; (b) in turn, the *Maximum accessibility distance* highlights the condition faced by the worst-served users; and (c) the *Cumulative distribution of accessibility distances* provides insights into the spatial distribution of accessibility, expressed as the fraction of users within specific distance thresholds d from the nearest collection facility.

Availability indicators assess the adequacy of collection facility supply relative to the number of users:

(d) The *Percentage of served population* represents the fraction of the population living in a municipality with at least one CC; and (e) the *Provider-to-population ratio* measures the total number of CCs per unit of population (typically per 100,000 inhabitants), providing insights into the density of collection facilities relative to population size.

Table 1 presents the mathematical formulation of the five indicators. Here, set I comprises discrete nodes representing potential user locations (e.g., residential addresses of households). Set J represents the current locations of CCs. Each node i in I is associated with a population value denoted as p_i, while d_{ij} symbolises the distances between pairs of nodes i in I and CCs at locations j in J. Furthermore, municipalities are denoted by set M, where the sets of users' nodes and collection facilities within each municipality m are represented as $I_m \subseteq I$ and $J_m \subseteq J$.

The indicators can be calculated at various geographical levels. Bruno et al. (2021) refer to the Nomenclature of Territorial Units for Statistics (NUTS) classification, specifically NUTS-2 and NUTS-3 levels corresponding to provinces and districts, respectively. By differentiating demand nodes and facilities according to these administrative subdivisions, the methodology enables a nuanced analysis of spatial access to WEEE networks tailored to specific territorial units.

2.2. The Bavarian case

Bavaria, Germany's largest federal state by area, has a well-structured administrative system that helps manage and implement waste collection across the region. At the highest level, Bavaria has seven provinces ($|P| = 7$): *Upper Bavaria*, *Lower Bavaria*, *Upper Palatinate*, *Upper Franconia*, *Middle Franconia*, *Lower Franconia*, and *Swabia* (Appendix A.1). Each province is divided into districts, totalling 71 rural and 25 urban districts ($|D| = 96$). Following the NUTS classification, Bavaria as a whole is categorised at the NUTS-1 tier, with provinces and districts at the NUTS-2 and NUTS-3 tiers, respectively (Fig. 1). At the most granular level, districts are subdivided into municipalities. Notably, we confine the analysis to municipalities classified under the *Local Administrative Units* hierarchy (formerly NUTS-4 and NUTS-5). These include administrative cooperatives,[2] where several independent municipalities collaborate for administrative purposes, and independent municipalities,[3] reducing the number of entities considered at the municipal level in our study from > 2000 to $|M| = 1554$. The municipal, district, and provincial divisions, as well as GIS data (Shapefiles), are based on the German cadaster information system (ALKIS®) and retrieved from the Agency for Digitisation, High-Speed Internet and Surveying (2024).

According to Article 3 of the Bavarian Waste Management Act (1996/2021), the district administration is responsible for waste generated in its area and for fulfilling duties and tasks in the field of waste recovery and disposal. There are two main approaches to recovering recyclable waste. The first one involves direct collection from households. For WEEE, this service is available to only 44% of households in Bavaria as of 2022. The second approach involves a network of facilities comprising 1530 major CCs with dedicated personnel, specific opening hours, and accepted materials, as well as thousands of minor satellite collection points (Bavarian Environment Agency, 2022). However, a significant challenge for this study is posed by the lack of comprehensive data on the number of facilities that actually accept WEEE. To address this, we manually assessed and reviewed the official websites of each district in detail, identifying $|J| = 1441$ CCs that generally accept WEEE. Adding to the complexity, e-waste is categorised into six groups under Article 2 of the Electrical and Electronic Equipment Act (2015/2022), and not all WEEE categories are accepted at every CC. However, this differentiation is not possible in the study at hand due to the limited available data.

This analysis is carried out at the district- instead of the province- or municipality-level. This restriction exists because the CC operation is funded through waste disposal fees paid by the residents of the district, therefore prohibiting inhabitants of one district from disposing of their waste in another district (Dornbusch et al., 2015). To further mitigate potential inaccuracies associated with spatial accessibility measures, we employ the most granular discretisation of Bavaria's population distribution, as illustrated for Swabia (7) in Fig. 1. This data is based on the 2022 census (released in June 2024; Federal Statistical Office, 2024) and encompasses an evaluation on grid cell-level (side length of 100 m) for all of Germany. The necessary data cleansing process refined the > 35 million records to $|I| = 564{,}670$ relevant tracts (with a population > 0) in Bavaria.

The collection rates per capita at the NUTS-3 level were provided by the Bavarian Environment Agency (2023) and are representative of 2022 (see Section 3.1). Notably, these collection rates cover WEEE collected from all sources, not exclusively from CCs. Furthermore, 16 district administrations have transferred their waste management obligations to special-purpose associations[4] per Article 5 of the Bavarian Waste Management Act (1996/2021) (cf. Appendix A.2). As a result, collection rates are only available at the level of these associations, assuming identical collection rates for the constituent districts. A detailed overview of the study area and the collection rates is provided in Supporting Information S1.

2.3. Data analysis

Three well-established statistical methods are employed to assess the relationship between the observed variables and to unveil spatial patterns:

(a) Spearman's Correlation (r) was selected for its non-parametric nature, offering robustness against outliers and non-linear relationships between variables. This method is used to evaluate the rank-order correlation between spatial indicators (availability and accessibility) and WEEE collection rates; (b) *Moran's I* measures global spatial autocorrelation and is used to identify clustering patterns in WEEE collection rates and spatial indicators, demonstrating whether similar values are

[2] German: *Verwaltungsgemeinschaften*

[3] German: *Einheitsgemeinden*

[4] German: *Zweckverbände*

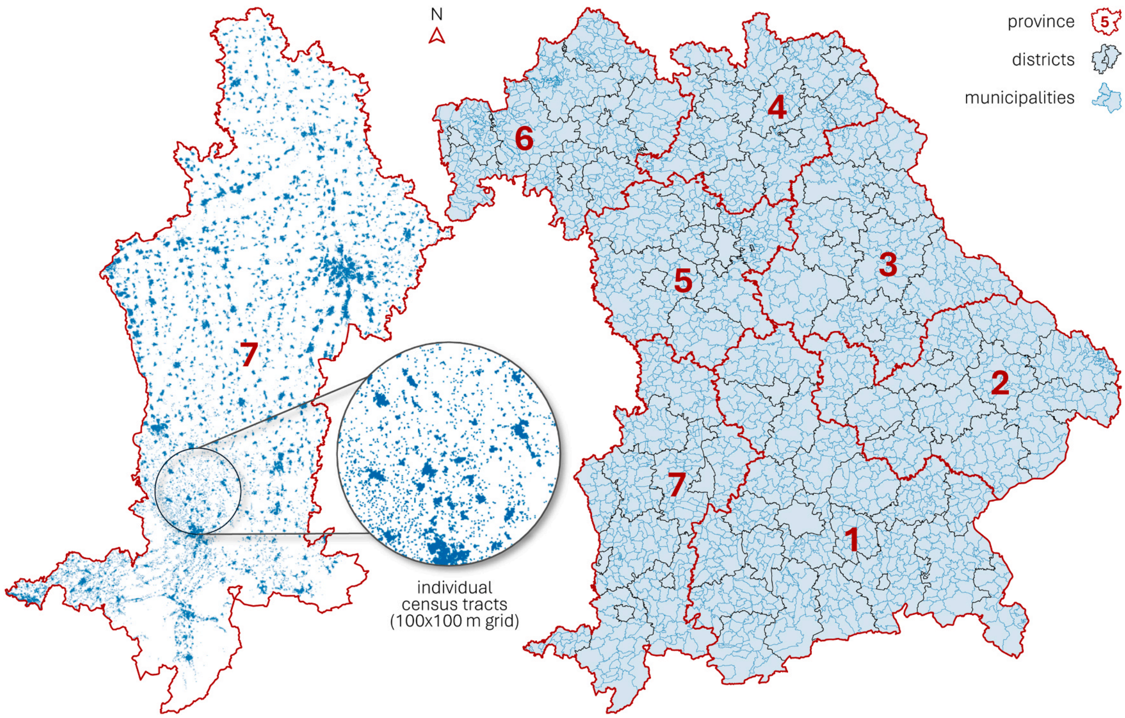

Fig. 1. Right side: Visualisation of administrative borders of provinces (red borders), districts (black borders), and municipalities (blue borders) in Bavaria. Left side: Exemplary 82,249 census tracts (blue dots) in the province of Swabia, where each point represents the existence of residents on a 100 m × 100 m grid.

geographically clustered, dispersed, or random; and (c) *Local Moran's I* provides detailed insights into specific clusters of high or low collection rates, identifying regional hotspots and outliers.

For this analysis, we use Python in the Jupyter Notebook environment, a platform that supports the integration of live code, visualisations, and narrative text. This approach relies on several Python libraries: GeoPandas provides functionalities for handling geometric data types, enabling us to perform spatial operations on geometric types such as points (e.g., census tract centroids) and polygons (e.g., administrative boundaries). Visualisation is carried out using Matplotlib, a versatile plotting library, augmented with Seaborn, to generate insightful statistical graphics. Additionally, SciPy and PySAL complement the toolset with extensive collections of scientific computing tools, particularly for statistical analysis. The combination of these libraries enables the manipulation, analysis, and visualisation of spatial data. Supporting Information S2 comprises the Jupyter Notebook (as a PDF), which documents the analysis, formulae, and methods used in this study. In detail, S2.1 covers the data import and cleansing process, while S2.2 contains the calculations for the spatial and statistical analyses. The Jupyter Notebook itself is also available for download on the Zenodo repository[5] to ensure transparency and enable reproducibility.

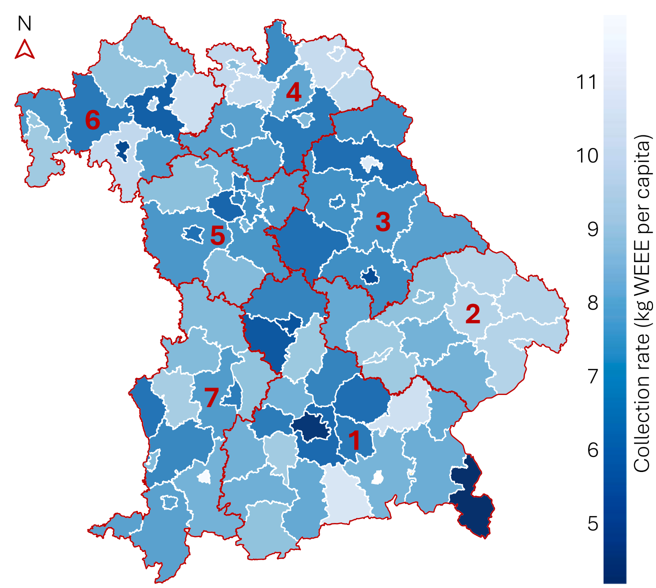

Fig. 2. District-specific WEEE collection rates.

3. Results and discussion

This section presents the results of the spatial analysis. All numerical results can be found in Supporting Information S1.

3.1. WEEE collection rates

Fig. 2 illustrates the distribution of collection rates for 2022 as provided by the Bavarian Environment Agency (2023). Here, the *City of Rosenheim* is a strong outlier at 17.89 kg WEEE per capita. This can arguably only be explained by external factors (e.g., influx from surrounding districts or commercial activities), which, however, could not be explained by the data or the experts consulted at the Bavarian Environment Agency. Since this outlier (with the other districts ranging from 4.16 kg in the *Berchtesgadener Land* to 11.89 kg in the *City of Kaufbeuren*) would significantly skew the distribution and impact the assessment and data clarity, we removed this data point from the dataset. The average collection rate thereafter is 7.86 kg per capita. Moran's I reveals a weak positive spatial autocorrelation (Moran's I = 0.085) of collection rates, suggesting a slight clustering of districts with similar collection rates; however, the p-value ($p \approx 0.11$) and z-score ($z \approx 1.25$) indicate that this clustering is not statistically significant. This suggests that collection performance in Bavaria is not informed by

[5] DOI: 10.5281/zenodo.14007947

broader geographical trends but rather by factors such as municipal management strategies.

3.2. Accessibility indicators

Fig. 3 *(A-C)* presents the results for the three accessibility indicators. The *average accessibility distance* (Fig. 3*A*) across all districts is 2.94 km, with values ranging from 1.19 km to 16.07 km. The *maximum accessibility distance* (Fig. 3*B*) shows a wide distribution, with an average of 9.99 km, a minimum of 4.08 km, and a maximum of 34.01 km, suggesting the presence of potential outliers.

Complementary, Fig. 3 *(D-F)* displays the results of Local Moran's I, highlighting identifiable clusters. High-high and low-low clusters indicate regions with consistently high or low accessibility, respectively. In contrast, low-high and high-low clusters indicate outliers where high-performance areas border low-performance areas. Evidently, districts with high accessibility distances are concentrated in northern Bavaria. Moran's I reveals a moderate (Moran's I = 0.295) and a slight (Moran's I = 0.130) positive spatial autocorrelation for *average* (Fig. 3*D*) and *maximum accessibility distances* (Fig. 3*E*), respectively, suggesting a discernible clustering of districts with similar average and maximum distances. P-value ($p \approx 0.002$) and z-score ($z \approx 4.37$) confirm the statistical significance of this observation for the average distances, while they remain ambiguous for the maximum distances ($p \approx 0.04$, $z \approx 1.88$).

Lastly, the *cumulative distribution of accessibility distances* expresses the proportion of users within specific distance thresholds from the nearest collection facility. In Fig. 3*C*, the covered population is shown for a threshold distance of 5.00 km. In addition, the histogram in Fig. 4 shows the results of a parameter study comprising multiple distances ($\bar{d}$ = [2.00 km, 3.00 km, 4.00 km, 5.00 km]), which reveals that, on average, 44.83% of the population has access to a CC within a 2.00 km radius (Figs. 4*A*) and 83.61% are within 5.00 km (Fig. 4*D*), in many municipalities even more than 95% (see Supporting Information S1). This also illustrates the low correlation between accessibility and collection rates: Unlike in the Italian case study, where distance was a barrier, the Bavarian collection infrastructure is closer to a hypothesised saturation point or 'baseline' where physical proximity is no longer the limiting factor for citizens. Moran's I analysis shows a moderate positive spatial autocorrelation (Moran's I = 0.231), again suggesting a statistically significant ($p \approx 0.004$ and $z \approx 3.21$) clustering of districts with similar indicator values. Local Moran's I indicates significant spatial patterns, with low-low clusters prevalent in the northern regions,

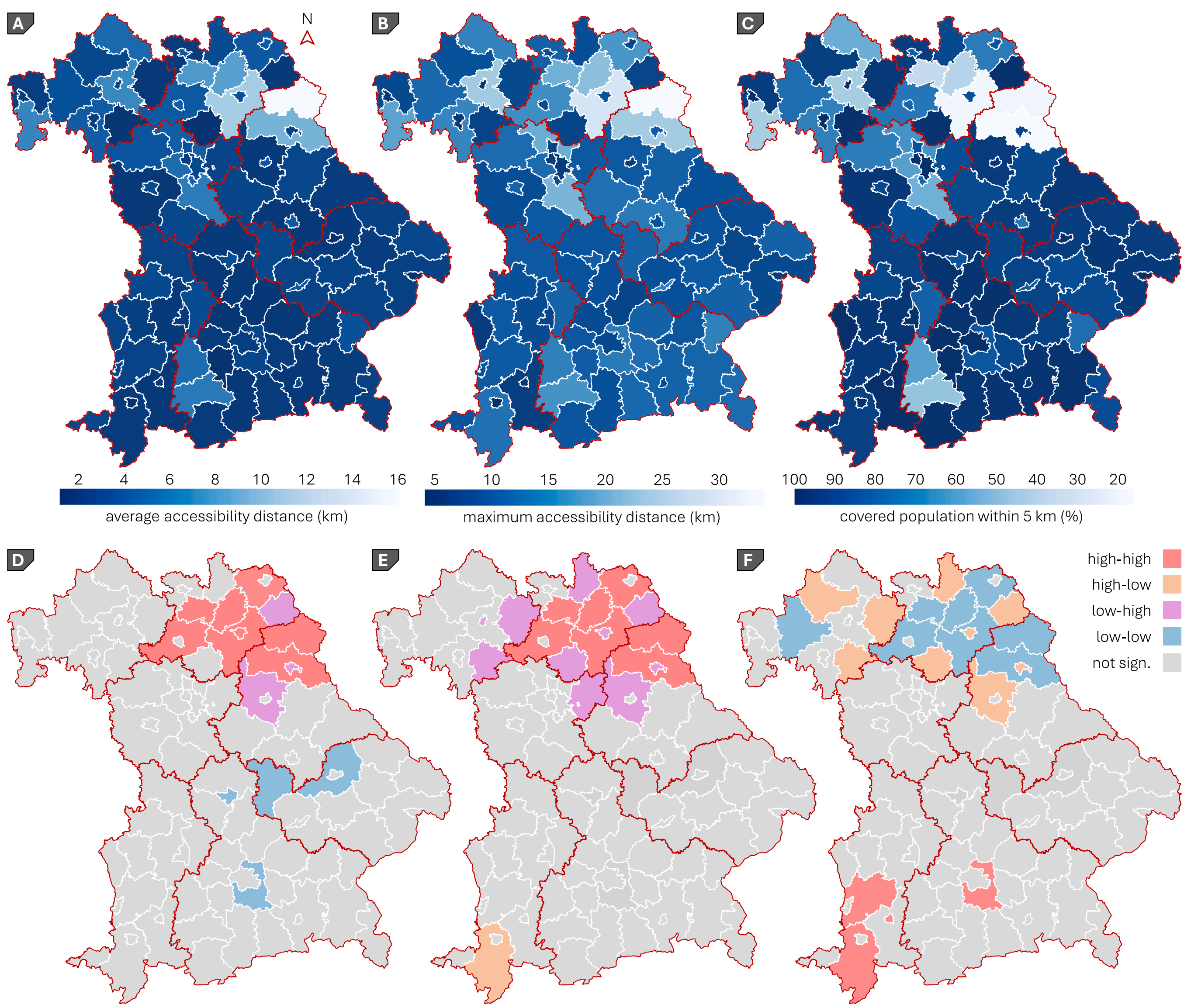

Fig. 3. Distribution of average (A) and maximum (B) accessibility distances as well as the covered population (C) and corresponding clusters as identified by Local Moran's I (D-F) per district.

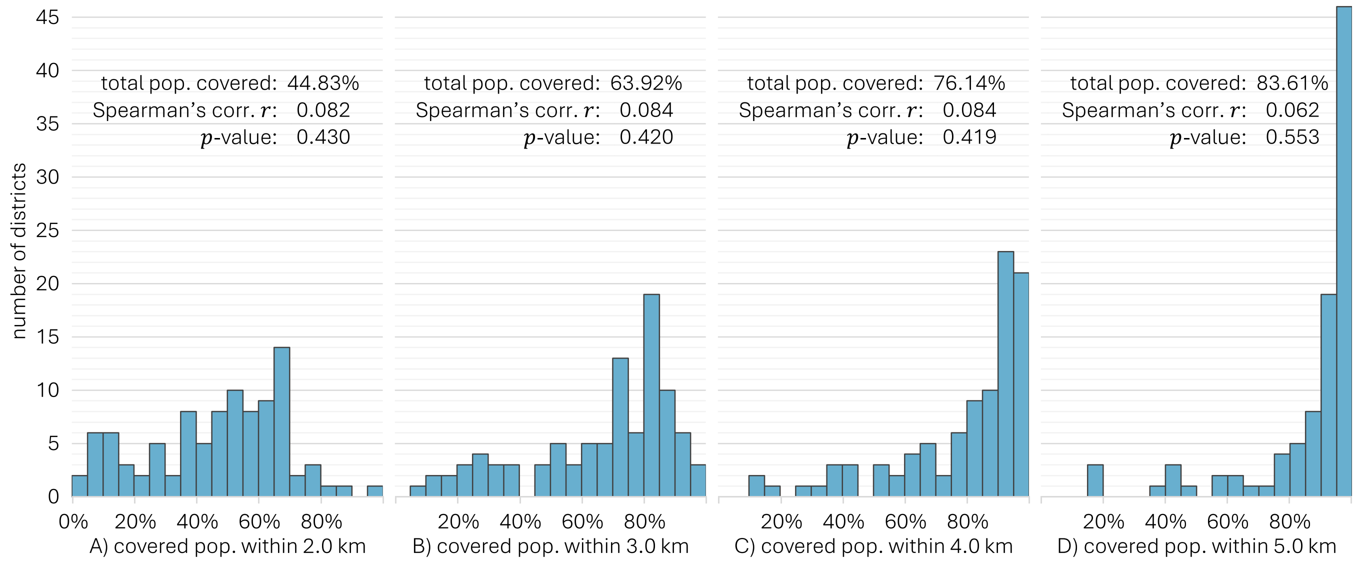

Fig. 4. Distribution of covered population for different threshold distances (A-D), as well as Spearman correlation coefficients and corresponding p-values for the relationship between various threshold distances and collection rates.

surrounded by high-low outliers (Fig. 3*F*). In these northern regions, we further note a slight but visible difference in accessibility between rural and urban districts. This discrepancy can be attributed to variations in population density between the countryside and cities.

Furthermore, we conduct a correlation analysis to elucidate the relationship between the *average* and *maximum accessibility distances* and collection rates (Fig. 5). For this purpose, due to a right-skewness of the data and to enhance pattern visibility and result interpretation, we apply a logarithmic transformation. The analysis reveals a marginally negative Spearman's correlation for average ($r = -0.089$) and maximum ($r = -0.072$) distances, indicating that an increase in the average distance corresponds to a slight reduction in collection rates. However, the correlation appears weak, with the p-values ($p = 0.394$ and 0.490, respectively) not meeting the significance threshold (5%). Fig. 4 shows a similarly weak and non-significant correlation for the distribution of covered population at all examined thresholds. Thus, it is plausible that all of the observed relationships are merely coincidental. This assessment implies that none of these variables possesses a robust predictive capacity for WEEE collection performance.

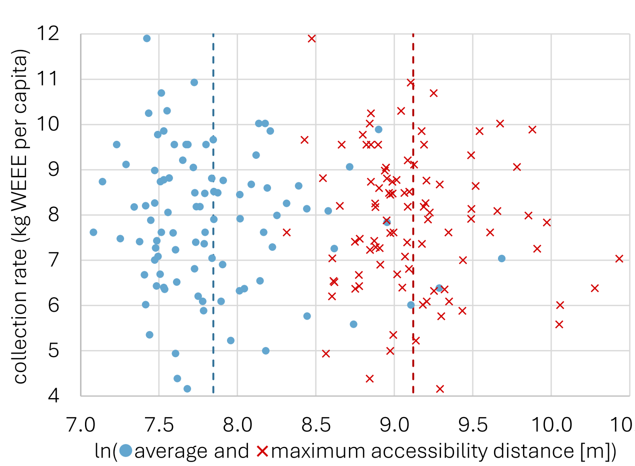

Fig. 5. Correlations between accessibility distances and WEEE collection rates. Abscissa: average (blue dots) and maximum (red crosses) accessibility distance (logarithmised) as well as respective averages. Ordinate: Collection rate.

3.3. *Availability indicators*

Fig. 6 *(A-B)* presents the computational results for the two availability indicators. Both indicators show considerable heterogeneity across districts. Moran's I results in a weak positive spatial autocorrelation for both the *percentage of served population* (Fig. 6*A*) and the *provider-to-population ratio* (Fig. 6*B*; Moran's $I = 0.107$ and 0.099, respectively), suggesting a slight tendency for districts with similar availability indicators to cluster together. However, the p-values ($p \approx 0.07$ and 0.08, respectively) and z-scores ($z \approx 1.53$ and 1.41, respectively) would suggest that this clustering is not significant at the 5% level. Interestingly, based on Local Moran's I, various urban districts in northern Bavaria emerge as high-low outliers in terms of the *percentage of served population* (Fig. 6*C*), statistically signifying superior percentages in cities compared to rural areas, and districts with high *provider-to-population ratio* (Fig. 6*D*) values in central Bavaria are clustered together. It can be observed that differences between urban and rural districts for the *provider-to-population ratio* are inversely related to the *percentage of served population*.

Correlating the *percentage of served population* with collection rates reveals a weak positive ($r = 0.022$) but insignificant ($p = 0.830$) correlation (cf. Fig. 7). Interestingly, the *provider-to-population ratio* is the only of the five indicators with a statistically significant ($p = 0.038$) and moderately positive correlation ($r = 0.213$) with collection rates.

In summary, the in-depth examination reveals regional disparities in WEEE management infrastructure in Bavaria, with the northern districts generally displaying poorer indicator values than their southern counterparts. Analyses using Moran's I and Local Moran's I confirm these spatial patterns and demonstrate statistically significant clustering. In areas with higher population density, mainly urban districts, we observe better spatial accessibility than rural districts. However, rural districts feature better availability of CCs in terms of the *provider-to-population ratio*. However, despite these demonstrated disparities, only one of the five accessibility and availability indicators shows a statistically significant correlation. These results contrast with the Italian case study by Bruno et al. (2021), which identifies broader regional and contextual differences in the factors influencing e-waste collection rates. While distance is a likely barrier in Italy, building more collection centres to reduce the average distance of 2.94 km would thus likely result in diminishing returns in Bavaria.

The shown fact that accessibility and availability indicators are weak predictors of collection rates in Bavaria rules out a general

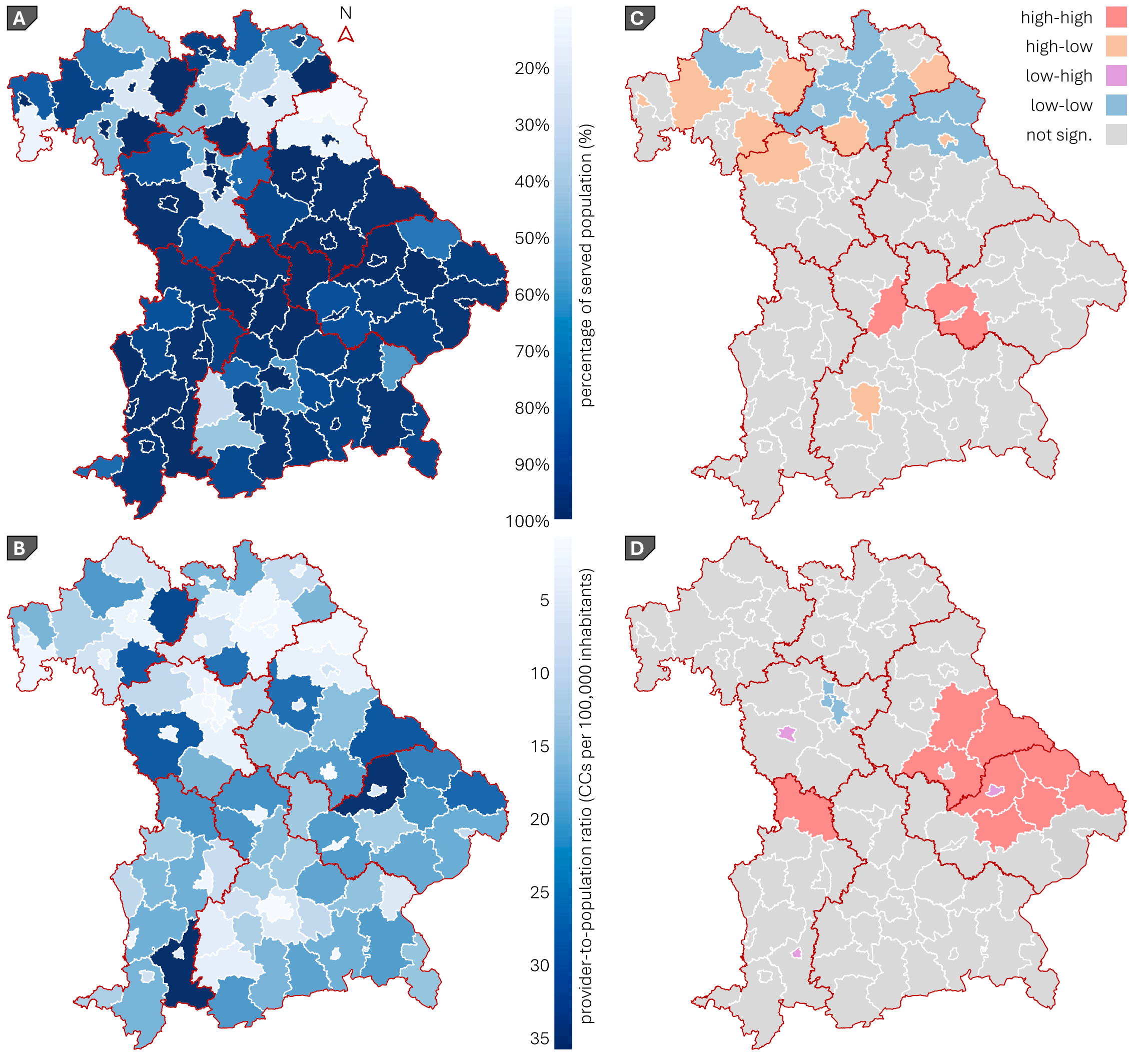

Fig. 6. Distribution of percentages of served population (A) and provider-to-population ratios (B) and corresponding clusters as identified by Local Moran's I (C-D) per district.

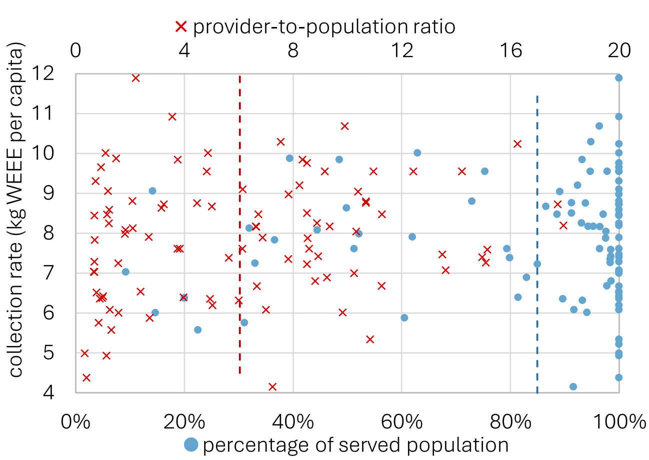

Fig. 7. Correlations between availability indicators. Primary (bottom) abscissa: percentages of served population (blue dots); secondary (top) abscissa: provider-to-population ratios (red crosses). Ordinate: collection rate.

transferability of the conclusions drawn from the Italian case. Research by Davies et al. (2002) supports the notion that demographics, here particularly education levels, are stronger predictors of recycling behaviour. Papaoikonomou et al. (2020), who evaluate WEEE recycling performance through a structured questionnaire, underscore the importance of psychological factors and public education in improving WEEE recycling rates. Applying the Theory of Planned Behaviour in this context, they show that the attitude towards WEEE recycling and willingness to pay are the most significant predictors of the intention to recycle. Other factors found to be influential include economic incentives, information, and subjective norms (cf. Echegaray and Hanstein, 2017; Aboelmaged, 2021). The fact that many urban municipalities (e.g., Munich or Nuremberg) with superior accessibility indicators report lower per-capita collection rates compared to many rural regions (e.g., Cham or Regen) supports the idea that, beyond a certain baseline, other factors (e.g., smaller living spaces, anonymity of disposal) dominate.

4. Contributions and limitations

In the Italian case, weak collection rate clusters in Italy's structurally and economically disadvantaged southern regions suggest the presence of spatial autocorrelation or dependence. By showing that the methodology yields different results in Bavaria's homogeneous waste management system compared to Italy's heterogeneous conditions, we provide empirical evidence that 'convenience' and the premise that more CCs equal higher collection rates are context-dependent. Our findings for the

Bavarian case imply that socio-economic variables may play a more significant role than spatial accessibility.

The finding that spatial accessibility and availability do not significantly correlate with WEEE collection performance could suggest that the current allocation of resources to recovery networks is not unequivocally efficient. In a recent study, likewise for the Bavarian case, Schmidt and Singh (2024) suggest that selectively closing 20% of recycling facilities could be possible without drastically reducing availability, freeing up resources that could instead be directed toward improving other influential factors (e.g., enhancing awareness, better education, providing more comprehensive public information, and introducing additional incentives, such as monetary rewards). This approach could drive higher WEEE collection performance and more effective waste management practices.

However, several limitations of the study at hand must be acknowledged. Particularly, this analysis focuses solely on CCs, simplifying the overall complexity of the WEEE management system in Bavaria, which also includes minor or satellite collection points, curbside collection, and especially collection through retailers, which were not considered in our study, so that it remains unclear what proportion of the overall collection rates can be attributed specifically to CCs. Additionally, the number and geographic locations of the WEEE-accepting CCs were assessed manually and lack official verification, and we did not distinguish between different kinds of WEEE, even though some CCs might.

Lastly, our results show that the common notion that 'convenience', as motivated in the introduction, can be operationalised solely by spatial distance is challenged. Not only does the concept of convenience in waste disposal decisions lacks a precise definition (Wagner, 2013), convenience may also encompass factors such as the attractiveness of the site, the range of accepted materials (Zaharudin et al., 2021) ease of access (e.g., by public transportation), sorting requirements, operating hours, and proximity to other activities such as retail or leisure facilities, which could not be accounted for in this study. The fact that the *provider-to-population-ratio* is the only indicator significantly correlated with collection rates supports this notion.

5. Conclusion

By transferring the method presented by Bruno et al. (2021) for the Italian case, the study at hand quantifies spatial accessibility and availability indicators for collection centres in the German federal state of Bavaria. We find that, unlike in Italy, accessibility and availability do not significantly correlate with collection rates, implying that additional collection centres would not substantially increase collection rates. This is likely due to Bavaria's relative internal homogeneity (although we identify clusters in Bavaria as well) and high coverage of collection centres, which contrast with Italy's north-south divide in infrastructure and collection rates. Given that meeting the EU's recycling targets remains a challenge for Germany, the results strongly suggest the need for incentives and measures to increase collection rates, beyond improving accessibility and availability.

Based on the insights and limitations discussed, numerous pathways for future research could further our understanding of indicators for WEEE collection performance. Future studies could incorporate additional collection methods into the analysis to provide a more comprehensive picture of the WEEE management system in Bavaria. Another important avenue for future research is to address spatial autocorrelation. In our study, we observed moderate spatial patterns in the distribution of CCs and their performance. However, spatial autocorrelation, where locations close to each other are more likely to have similar values, can influence the interpretation of results. The study by Bruno et al. (2021), where weak clusters of similar collection rates influence results in the southern regions of Italy, would suggest this implication. The observation that collection performance in Bavaria is not driven by broader geographical trends but is highly locally specific suggests a strong potential for sharing best practices in municipal WEEE management and could benefit from an in-depth analysis of municipality-specific success factors. Future research could also benefit from employing statistical techniques to handle spatial dependence, such as spatial regression models or geographically weighted regression. These methods would enable a more precise analysis of the observed patterns, leading to more accurate and reliable conclusions.

CRediT authorship contribution statement

Lukas Messmann: Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Kaan Senoglu:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the Bavarian Environment Agency (LfU) for providing us with data on collection rates, without which this study could not have been carried out. We are also deeply grateful to Anne Hajdu for her diligent assistance and excellent input.

Appendix A

Table A.1
Characteristics of the study area (Federal Statistical Office, 2024; cf. Supporting Information S1)

ID	Provinces	Population	Census tracts	Districts	Municipalities	CCs
	P	*Inhabitants*	$\|I\|$	$\|D\|$	$\|M\|$	$\|J\|$
1	Upper Bavaria	4,672,141	156,941	23	398	414
2	Lower Bavaria	1,228,139	89,096	12	209	232
3	Upper Palatinate	1,097,628	64,702	10	167	157
4	Upper Franconia	1,044,345	56,103	13	196	98
5	Middle Franconia	1,773,944	60,893	12	166	125
6	Lower Franconia	1,307,253	54,686	12	229	150
7	Swabia	1,889,769	82,249	14	189	265
Total		13,013,219	564,670	96	1554	1441

Table A.2
Collection rates within special-purpose associations in Lower Bavaria, Upper Franconia, and Swabia

ID	Province	Special-purpose association	District	Collection rate
				kg WEEE / capita
2	Lower Bavaria	*ZAW Donau-Wald*	City of Passau	9.55
			District Deggendorf	9.55
			District Freyung-Grafenau	9.55
			District Passau	9.55
			District Regen	9.55
		ZAW Straubing	City of Straubing	8.73
			District Straubing-Bogen	8.73
		AWV Isar-Inn	District Dingolfing-Landau	8.18
			District Rottal-Inn	8.18
4	Upper Franconia	*AZV Hof*	City of Hof	10.02
			District Hof	10.02
7	Swabia	*Nordschwäbischer AWV*	District Dillingen	8.48
			District Donau-Ries	8.48
		ZAK	City of Kempten (Allgäu)	7.61
			District Lindau (Bodensee)	7.61
			District Oberallgäu	7.61

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2026.100515.

Data availability

Link to the full dataset (Jupyter Notebook) as an external item: Measuring Spatial Access to Recovery Networks for WEEE: The Bavarian Case (Zenodo)

References

Aboelmaged, M., 2021. E-waste recycling behaviour: an integration of recycling habits into the theory of planned behaviour. J. Clean. Prod. 278, 124182. https://doi.org/10.1016/j.jclepro.2020.124182.

Agency for Digitisation , High-Speed Internet and Surveying (2024). ALKIS®-Verwaltungsgebiete. ⟨https://geodaten.bayern.de/opengeodata/OpenDataDetail.html?pn=verwaltung⟩. (last accessed 05 December 2025).

Andeobu, L., Wibowo, S., Grandhi, S., 2021. A systematic review of e-waste generation and environmental management of Asia Pacific countries. Int. J. Environ. Res. Public Health 18 (17), 9051. https://doi.org/10.3390/ijerph18179051.

Andrade, D.F., Romanelli, J.P., Pereira-Filho, E.R., 2019. Past and emerging topics related to electronic waste management: top countries, trends, and perspectives. Environ. Sci. Pollut. Res. 26, 17135–17151. https://doi.org/10.1007/s11356-019-05089-y.

Baldé, C.P., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., Bel, G., Deubzer, O., Fernandez-Cubillo, E., Forti, V., Gray, V., Herat, S., Honda, S., Iattoni, G., Khetriwal, D.S., Luda di Cortemiglia, V., Lobuntsova, Y., Nnorom, I., Pralat, N., Wagner, M., 2024. Global E-waste Monitor 2024. International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR). Geneva/Bonn. ⟨http://handle.itu.int/11.1002/pub/8224ef17-en⟩. (Last accessed 05 December 2025).

Bavarian Environment Agency (LfU). 2022. Hausmüll in Bayern – Bilanzen 2022. Bayerisches Landesamt für Umwelt (LfU). ⟨https://www.abfallbilanz.bayern.de/doc/2022/Abfallbilanz2022.pdf⟩. (last accessed 05 December 2025).

Bavarian Environment Agency (LfU). 2023. Personal email communication, 15 December 2023. ⟨www.lfu.bayern.de⟩.

Bavarian Waste Management Act. 1996/2021. Bavarian Waste Management Act (Bayrisches Abfallwirtschaftsgesetz – BayAbfG) in the version of the announcement of August 9, 1996 (GVBl. p. 396, 449, BayRS 2129-2-1-U), which was last amended by § 2 of the law of May 25, 2021 (GVBl. p. 286). ⟨https://www.gesetze-bayern.de/Content/Document/BayAbfAlG/True⟩. (last accessed 05 December 2025).

Boldoczki, S., Thorenz, A., Tuma, A., 2021. Does increased circularity lead to environmental sustainability?: The case of washing machine reuse in Germany. J. Ind. Ecol. 25 (4), 864–876. https://doi.org/10.1111/jiec.13104.

Bruno, G., Diglio, A., Passaro, R., Piccolo, C., Quinto, I., 2021. Measuring spatial access to the recovery networks for WEEE: an in-depth analysis of the Italian case. Int. J. Prod. Econ. 240, 108210. https://doi.org/10.1016/j.ijpe.2021.108210.

Chi, X., Wang, M.Y., Reuter, M.A., 2014. E-waste collection channels and household recycling behaviours in Taizhou of China. J. Clean. Prod. 80, 87–95. https://doi.org/10.1016/j.jclepro.2014.05.056.

Davies, J., Foxall, G.R., Pallister, J., 2002. Beyond the intention–behaviour mythology: an integrated model of recycling. Mark. Theory 2 (1), 29–113. https://doi.org/10.1177/14705931020020016.

Directive 2002/96/EC. (2002). Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). ⟨https://eur-lex.europa.eu/eli/dir/2002/96/oj⟩. (last accessed 05 December 2025).

Directive (EU) 2024/884. 2024. Directive (EU) 2024/884 of the European Parliament and of the Council of 13 March 2024 amending Directive 2012/19/EU on waste electrical and electronic equipment (WEEE). ⟨https://eur-lex.europa.eu/eli/dir/2024/884/oj⟩. (last accessed 05 December 2025).

Dornbusch, H.-J., Faßbender, K., Gebken, W., Halm, G., Höppner, T., Hunger, G., Lubina-Hermann, B., Neubauer, A., Regener, D., 2015. Der kommunale Wertstoffhof – Bestandsaufnahme und Ausblick. Verband kommunaler Unternehmen e.V. (VKU). ⟨https://www.vku.de/fileadmin/user_upload/Verbandsseite/Publikationen/2015/VKU_Broschu_re-Wertstoffhof_Web-DS.PDF⟩. (last accessed 05 December 2025).

Echegaray, F., Hansstein, F.V., 2017. Assessing the intention-behaviour gap in electronic waste recycling: the case of Brazil. J. Clean. Prod. 142, 180–190. https://doi.org/10.1016/j.jclepro.2016.05.064.

Electrical and Electronic Equipment Act. 2015/2022. Electrical and Electronic Equipment Act of October 20, 2015 (BGBl. I p. 1739), which was last amended by Article 1 of the law of December 8, 2022 (BGBl. I p. 2240). ⟨https://www.gesetze-im-internet.de/elektrog_2015/⟩. (last accessed 05 December 2025).

Eurostat. 2024. Waste electrical and electronic equipment (WEEE) by waste management operations - open scope, 6 product categories (from 2018 onwards). https://doi.org/10.2908/ENV_WASELEEOS.

Favot, M., Grassetti, L., 2017. E-waste collection in Italy: results from an exploratory analysis. Waste Manag. 67, 222–231. https://doi.org/10.1016/j.wasman.2017.05.026.

Federal Statistical Office. 2024. Census 2022 – Census results – Grid data for download for geographical information systems (GIS). ⟨https://www.zensus2022.de/EN/Census_results/_inhalt.html⟩. (last accessed 05 December 2025).

Ghisellini, P., Quinto, I., Passaro, R., Ulgiati, S., 2023. Circular economy management of waste electrical and electronic equipment (WEEE) in Italian urban systems: comparison and perspectives. Sustainability 15 (11), 9054. https://doi.org/10.3390/su15119054.

Gonda, L., D'Ans, P., Degrez, M., 2019. A comparative assessment of WEEE collection in an urban and rural context: case study on desktop computers in Belgium. Resour. Conserv. Recycl. 142, 131–142. https://doi.org/10.1016/j.resconrec.2018.11.008.

Ibanescu, D., Cailean (Gavrilescu), D., Teodosiu, C., Fiore, S., 2018. Assessment of the waste electrical and electronic equipment management systems profile and sustainability in developed and developing European Union countries. Waste Manag. 73, 39–53. https://doi.org/10.1016/j.wasman.2017.12.022.

Iyer, E.S., Kashyap, R.K., 2007. Consumer recycling: role of incentives, information, and social class. J. Consum. Behav. Int. Res. Rev. 6 (1), 32–47. https://doi.org/10.1002/cb.206.

Laeequddin, M., Kareem Abdul, W., Sahay, V., Tiwari, A.K., 2022. Factors that influence the safe disposal behavior of e-waste by electronics consumers. Sustainability 14 (9), 4981. https://doi.org/10.3390/su14094981.

Messmann, L., Helbig, C., Thorenz, A., Tuma, A., 2019. Economic and environmental benefits of recovery networks for WEEE in Europe. J. Clean. Prod. 222, 655–668. https://doi.org/10.1016/j.jclepro.2019.02.244.
Papaoikonomou, K., Latinopoulos, D., Emmanouil, C., Kungolos, A., 2020. A survey on factors influencing recycling behaviour for waste of electrical and electronic equipment in the municipality of Volos, Greece. Environ. Process. 7, 321–339. https://doi.org/10.1007/s40710-019-00399-2.
Penchansky, R., Thomas, J.W., 1981. The concept of access: definition and relationship to consumer satisfaction. Med. Care 19 (2), 127–140.
Schmidt, M., Singh, B., 2024. Selectively closing recycling centres in Bavaria: reforming waste-management policy to reduce disparity. Networks 84 (2), 148–160. https://doi.org/10.1002/net.22221.
Shahabuddin, M., Uddin, M.N., Chowdhury, J.I., Ahmed, S.F., Uddin, M.N., Mofijur, M., Uddin, M.A., 2023. A review of the recent development, challenges, and opportunities of electronic waste (e-waste). Int. J. Environ. Sci. Technol. 20 (4), 4513–4520. https://doi.org/10.1007/s13762-022-04274-w.
Shevchenko, T., Laitala, K., Danko, Y., 2019. Understanding consumer E-waste recycling behavior: introducing a new economic incentive to increase the collection rates. Sustainability 11 (9), 2656. https://doi.org/10.3390/su11092656.
Thukral, S., Shree, D., Singhal, S., 2023. Consumer behaviour towards storage, disposal and recycling of e-waste: systematic review and future research prospects. Benchmark. Int. J. 30 (3), 1021–1072. https://doi.org/10.1108/BIJ-12-2021-0774.
Wagner, T.P., 2013. Examining the concept of convenient collection: an application to extended producer responsibility and product stewardship frameworks. Waste Manag. 33 (3), 499–507. https://doi.org/10.1016/j.wasman.2012.06.015.
Walther, G., Steinborn, J., Spengler, T.S., Luger, T., Herrmann, C., 2010. Implementation of the WEEE-directive—economic effects and improvement potentials for reuse and recycling in Germany. Int. J. Adv. Manuf. Technol. 47, 461–474. https://doi.org/10.1007/s00170-009-2243-0.
Zaharudin, Z.A., Brint, A., Genovese, A., Piccolo, C., 2021. A spatial interaction model for the representation of user access to household waste recycling centres. Resour. Conserv. Recycl. 168, 105438. https://doi.org/10.1016/j.resconrec.2021.105438.
Zhang, S., Zhang, M., Yu, X., Ren, H., 2016. What keeps Chinese from recycling: accessibility of recycling facilities and the behaviour. Resour. Conserv. Recycl. 109, 176–186. https://doi.org/10.1016/j.resconrec.2016.02.008.