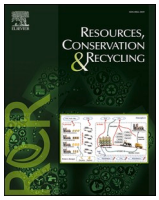
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Review



A systematic scoping review of solid waste sampling and manual analyses, focusing on assessing mechanical waste processing

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ABSTRACT

In the context of a circular economy, the use of secondary raw materials from municipal solid waste (MSW) is gaining importance. To produce preconcentrates and facilitate material recycling, mechanical waste processing (MWP) is applied. Sampling and manual analysis are commonly used to assess MWP, supporting a wide range of applications, including environmental assessments, process optimization, and the determination of material recovery potential. However, to date, no comprehensive literature overview exists of the sampling and manual analysis of MSW, with a specific focus on MWP assessment. To address this gap, a scoping review was conducted based on systematic search criteria. In total, more than 12,000 English- and German-language publications were screened, resulting in a comprehensive overview of current standards, methods, and practical applications. The results revealed methodological and terminological heterogeneity, underscoring the need for harmonized specifications in the waste management sector. As an initial step, approaches, terminology, and relevant criteria that may support the development of frameworks for MSW sampling and manual analysis to assess MWP were contextualized. Therefore, this scoping review supports improved planning and execution of sampling campaigns. This, in turn, leads to more accurate and comparable data, thereby contributing to a more quantifiable circular economy.

1. Introduction

With the concept of a circular economy becoming increasingly popular in recent decades, waste is now recognized as the key raw material for our economy. Mechanical waste processing (MWP) is crucial to extract secondary raw materials from municipal solid waste (MSW) (Pretz et al., 2020), whereas efficient management of MWP is essential to closing material loops. MWP can generally be subdivided into the fundamental unit operations of comminution, particle-size classification, and sorting (Pretz et al., 2020). Depending on the input waste streams and the desired output(s), different MWP operations (as single operations or combined in plants) are used (Christensen, 2011). Although approaches to the MWP of mixed MSW have existed since the 1970s, the implementation of MWP plants has intensified, particularly since the 1990s (Christensen, 2011). The development can be attributed to several driving factors (e.g., technical (Christensen, 2011) and political (Letcher, 2020)), which have increasingly shifted attention toward optimized MWP of different waste streams (Cimpan et al., 2015).

In the treatment of mixed MSW, mechanical–biological treatment (MBT) plants are frequently used, which typically generate an organic-rich fraction for subsequent biological treatment, along with a high-calorific output stream suitable for energy recovery (Pretz et al.,

Abbreviations: CDW, Construction and demolition waste; GS, Google Scholar; LWP, Lightweight packaging waste; MBT/BMT, Mechanical-biological/biological-mechanical treatment; MRF, Material recovery facility; MSW, Municipal solid waste; MWP, Mechanical waste processing; rMSW, Residual municipal solid waste; ORKG, Open Research Knowledge Graph; PPWR, Packaging and Packaging Waste Regulation (EU) 2025/40; RQ, Research question; SC MSW, Selectively collected municipal solid waste; SR, Search string; SRF, Solid recovered fuel; SQ, Search question; RDF, Refuse-derived fuel; TOS, Theory of sampling (Gy's sampling theory); WEEE, Waste of electrical and electronic equipment; WoS, Web of Science.

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2020). Selectively collected (SC) MSW (such as paper, plastics, and metals), may be collected as mono-material streams or as mixed recyclables (Cimpan et al., 2015), and are often treated using two consecutive MWP plants (Pretz et al., 2020). In such configurations, the first MWP plant enables conditioning of waste properties and the production of pre-concentrates, while the second MWP plant focuses on producing secondary raw materials (Pretz et al., 2020). For glass and biowaste, these two MWP stages are frequently integrated within a single plant (Pretz et al., 2020). In addition, approaches exist for recovering recyclable materials from mixed MSW streams (Cimpan et al., 2015), which may result in three MWP stages (e.g., for packaging waste) (Letcher, 2020). Within MWP plants, a distinction is commonly made between pre-conditioning (e.g., particle size classification, air classification, ballistic separation) and subsequent sorting steps (Küppers et al., 2022). Pre-conditioning is a key prerequisite for effective downstream sorting processes (Küppers et al., 2022), especially for sensor-based sorting technologies, whose importance has increased significantly in recent years (Kroell et al., 2022).

To assess MWP operations or plants, sampling and manual analysis are frequently applied, serving an increasingly broad range of purposes. This includes the provision of robust data for environmental assessments (Köhler et al., under review), the evaluation of process performance for optimization (Araújo Morais et al., 2008), and the development of adapted treatment methods (Kim et al., 2014). Moreover, assessing MWP by sampling and manual analysis is used for the validation of sensor-based material flow characterization (Kroell et al., 2024) and process modeling approaches (Tanguay-Rioux et al., 2022), as well as the assessment of overall system efficiency and technically achievable recovery potentials (Blasenbauer et al., 2024). In addition, sampling of MWP can offer several advantages compared to other sampling points (e.g., sampling from households), as mechanical processing tends to homogenize output streams relative to the input, and access to the statistical population is improved through sampling from conveyor belts (Zwisele, 2005b).

Waste generally poses a challenge for sampling due to high material heterogeneity (e.g., (Arnold and Born, 2001; Brokaw and Hornberger, 1996; Lagerkvist et al., 2011; Rump and Scholz, 1988). In addition, many existing regulations for waste sampling focus on the sampling of waste containers, transport vehicles, or bulks/lots (e.g., (ASTM D 5658-20, 2020-12-00; ASTM D 5231-92, 1992 – Reapproved 2024-06-00; OENORM S 2127, 2024-07-00; Dahlén and Lagerkvist, 2008; European Commission, 2004; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014). For household waste sampling, overviews of existing literature are provided, e.g., by Sahimaa et al. (2015) and Dahlén and Lagerkvist (2008). A review of sensor-based material characterization of dry-mechanical recycling processes of non-hazardous waste can be found in Kroell et al. (2022). An overview of general statistical sampling concepts can, e.g., be found in Lohr (2019), and an overview of the Theory of Sampling can be found in Pitard (2019). However, to the best of the authors' knowledge, no comprehensive overview of sampling and manual analysis methods for assessing MWP has yet been provided.

In summary, despite its high relevance across a wide range of applications, the current literature does not yet offer a comprehensive overview of sampling and manual analysis methods that explicitly focus on assessing MWP. Therefore, this scoping review aims to consolidate the current state of the literature on the sampling and manual analysis of non-hazardous MSW for MWP assessment, focusing on identifying key concepts and definitions, describing prevailing research practices, and highlighting knowledge gaps. To this end, a systematic search strategy was developed, and n = 12,603 publications were screened, resulting in an overview of existing standards, methodological concepts, and practical applications (case studies). The objective is to provide a reliable foundation for improved planning and implementation of sampling campaigns of MWP, particularly for early-career researchers, and thereby enhance the quality and comparability of data generated. To address this research aim, the review is structured into four parts. First, relevant standards on MSW sampling are identified (Category 1). Second, scientific and gray literature on further methodological concepts related to the sampling and manual analysis of MSW is evaluated (Category 2). Both Categories 1 and 2 provide general methodological foundations for MSW sampling and manual analysis, which are subsequently examined with a specific focus on their relevance for assessing MWP. Third, case studies are reviewed to analyze the practical implementation of MWP sampling and to describe the current state of practice (Category 3). Finally, identified publications are contextualized, and implications for developing frameworks for MSW sampling and manual analysis to assess MWP are derived. Accordingly, the following three research questions (RQs) were defined:

RQ1: Which standards and further methodological concepts are available for the sampling and manual analysis of non-hazardous MSW, particularly with respect to their relevance for assessing MWP?

RQ2: How is the current practice in sampling and manual analysis of MWP characterized in the literature based on published case studies?

RQ3: How can the findings from RQ1 and RQ2 be contextualized, and what do they imply for developing frameworks for MSW sampling and manual analysis to assess MWP?

2. Material and methods

Sampling and manual analysis are frequently used to characterize MSW, resulting in a broad and diverse literature base that includes not only peer-reviewed articles but also gray literature such as standards and reports. Considering these diverse types of literature, the overall aim of the review was defined (cf. Section 1) and subsequently aligned with established review methodologies. Systematic reviews are often applied and typically used to answer narrowly defined research questions (Munn et al., 2018). However, since no prior literature compilation on sampling and manual analyses of non-hazardous MSW to assess MWP was identified, and the available literature was expected to be methodologically heterogeneous, alternative approaches were evaluated. One suitable approach found was the scoping review. Scoping reviews do not aim to produce a critically appraised and synthesized answer to a specific question; rather, they provide an overview of the existing evidence within a research field (Munn et al., 2018). They specifically aim to identify key concepts and definitions, describe how research is conducted in a given field, and highlight knowledge gaps (Arksey and O'Malley, 2005; Levac et al., 2010; Munn et al., 2018; Ritschl et al., 2016). These aims align closely with the intended scope of the present review. In addition, gray literature can be incorporated effectively (Ritschl et al., 2016). Therefore, the scoping review approach was selected.

Following Arksey and O'Malley (2005) and Peters et al. (2020), the scoping review was methodologically divided into five parts: 1. Identifying research questions (cf. Section 1), 2. Identifying relevant publications (cf. Section 2.1), 3. Selection of publications (cf. Section 2.2), 4. Data extraction (cf. Section 2.3), and 5. Collating, summarizing, and reporting the results (cf. Section 2.4). Limitations of the scoping review are outlined in Section 2.5. An overview of the applied search strategy is given in Figs. 1 and 2.

2.1. Identifying relevant studies

To answer the defined RQs, the scoping review was divided into two parts. In the first part, a review of available standards was conducted. In the second part, different databases were searched. All used search strings/queries were reviewed by five researchers from the field of waste management and applied during February 2025.

2.1.1. Standards review

The standards review was conducted using the search engine Nautos (DIN Media GmbH, 2025). The search engine was used with version

(a) Search strings for standards review

SR	Focus	Search String
SRA	Waste sampling	Free text search (waste OR rubbish OR garbage OR scrap OR trash OR litter) AND Title (English): (sampl*) NOT Title (English): (water) NOT Title (English): (soil)
SRB	Waste analyses	Free text search (waste OR rubbish OR garbage OR scrap OR trash OR litter) AND Title (English): (characteri* OR analy*) NOT Title (English): (water) NOT Title (English): (soil)

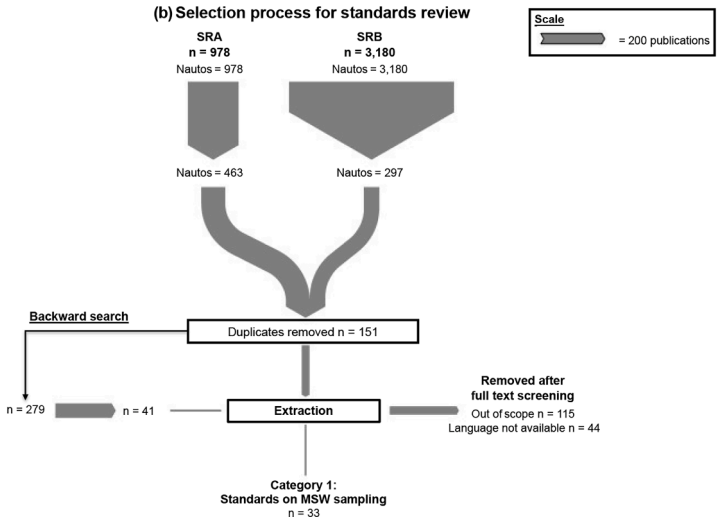


Fig. 1. Methodological approach for the standards review conducted using the Nautos search engine, with resulting publications classified as Category 1. (a) Search strings (SR) A and B applied in Nautos, and (b) the selection process for the identified publications.

2.0.2. An overview of the database scope, which can be accessed with bibliographic summaries, is available at DIN Software GmbH (2025). Two search strings (A and B) were defined (cf. Fig. 1(a)) without the use of additional search filters. Search string A focuses on the sampling, and search string B on the analysis of MSW. The search terms were applied to the standard text or title. Boolean operators (AND, OR) were used to capture synonyms, and wildcard operators (*) were applied to include different word endings as well as American and British spellings. Since this review focuses on MSW, standards with the terms "water" and "soil" in their titles were excluded. Secondary sources (cited publications) within the identified standards were additionally screened.

2.1.2. Database review

The second part of this scoping review focused mainly on scientific publications (i.e., peer-reviewed and non-peer-reviewed journal articles). The starting point was a selection of literature collected by the authors prior to the scoping review over the past years. The collected literature was sourced from other literature searches on related topics using Scopus, Google Scholar, or Web of Science. In addition, the literature was obtained through simple Google searches conducted by the authors themselves or by others (e.g., students) and through discussions with experts in the field of waste sampling and process analysis. Thereby, a basis was created to provide a relevant literature foundation and to define search strings and terms. The search strings/questions used, along with their respective focus areas, are listed in Fig. 2(a). With the defined search strings, three multidisciplinary databases (Scopus, Web of Science, and Google Scholar) were searched. Thereby, potential biases resulting from one specific database were reduced. Search strings with Boolean operators (AND, OR) and wildcard operators (*) were defined (cf. Fig. 2(a)). The search strings presented in Fig. 2(a) are adapted to the Scopus syntax. The search terms either refer to the title (TITLE) or the title, abstract, and keywords (TITLE-ABS-KEY). For Web of Science and Google Scholar, the search strings were adapted to the respective syntaxes. Additionally, the AI search engine Open Research Knowledge Graph (ORKG) Ask was utilized. Therefore, two search questions (SQ) were defined (cf. Fig. 2(a)), which focus on the sampling of waste sorting plants. The aim was to minimize potential biases introduced by the selected search terms and strings, as ORKG Ask employs a semantic search approach that differs from traditional literature databases (Technische Informationsbibliothek, 2025). ORKG Ask was selected due to its openly accessible source code, which enhances transparency and reproducibility relative to other AI-driven search approaches (Technische Informationsbibliothek, 2025). For all databases, searches were performed without imposing filters related to language or publication period.

Based on the identified publications in Scopus and Google Scholar after abstract screening, a **forward search** was conducted (i.e., screening of publications **that cited** the initially selected publication). Additionally, a **backward search** was performed with all publications after the full-text screening (i.e., screening publications that **were cited** by the initially selected publications). For this, Scopus was used where possible. Publications not included in Scopus were searched manually backwards. These approaches aimed to include publications that could not be identified through the defined search strings, terms, and queries. The identification of gray literature was ensured by including previously collected literature, forward and backward searches, and the use of Google Scholar and ORKG Ask.

2.2. Study selection

Using the described search strategy, a total of $n = 12{,}603$ publications were identified. The large number of initially identified publications resulted from less restrictive search terms, which were used to reduce terminological bias. To select relevant publications, a multi-stage selection process was applied (cf. Figs. 1(b) and 2(b)). An initial screening of the titles was conducted, followed by the abstracts, and finally the full texts. Since abstracts were not available for the standards, the full texts were screened directly. To ensure a reproducible selection of publications, inclusion and exclusion criteria were defined, which are described in the following sections.

2.2.1. Inclusion criteria

Only publications in German or English were considered for inclusion due to the authors' language proficiency. No exclusions were made based on the type of publication. Publications were included if they addressed the sampling of non-hazardous MSW. A distinction for

(a) Search strings for database review

SR	Focus	Search String
SR1	Sampling waste sorting process/plant	TITLE (waste OR rubbish OR garbage OR scrap OR trash OR litter) AND TITLE-ABS-KEY (assess* OR monitor* OR characteri* OR analy* OR eval* OR examin* OR supervis*) AND TITLE-ABS-KEY (sort*) AND TITLE-ABS-KEY (plant* OR facilit* OR process*) AND TITLE-ABS-KEY (sampl*)
SR2	Sampling waste processing process/plant	TITLE (waste OR rubbish OR garbage OR scrap OR trash OR litter) AND TITLE-ABS-KEY (assess* OR monitor* OR characteri* OR analy* OR eval* OR examin* OR supervis*) AND TITLE-ABS-KEY (process*) AND TITLE (plant* OR facilit*) AND TITLE-ABS-KEY (sampl*) AND NOT TITLE-ABS-KEY (sort*)
SR3	Waste sampling in plant	TITLE (waste OR rubbish OR garbage OR scrap OR trash OR litter) AND TITLE (sampl*) AND TITLE-ABS-KEY (plant* OR facilit* OR process*)
SR4	Sort/process waste	TITLE ("waste sort*" OR "waste process*") AND TITLE-ABS-KEY (sampl* OR survey* OR "data collection" OR testing OR "specimen collection")
SQ1	Assessing sorting plants	How to assess waste sorting plants?
SQ2	Assessing material recovery facilities	How to assess material recovery facilities?

(b) Selection process for database review

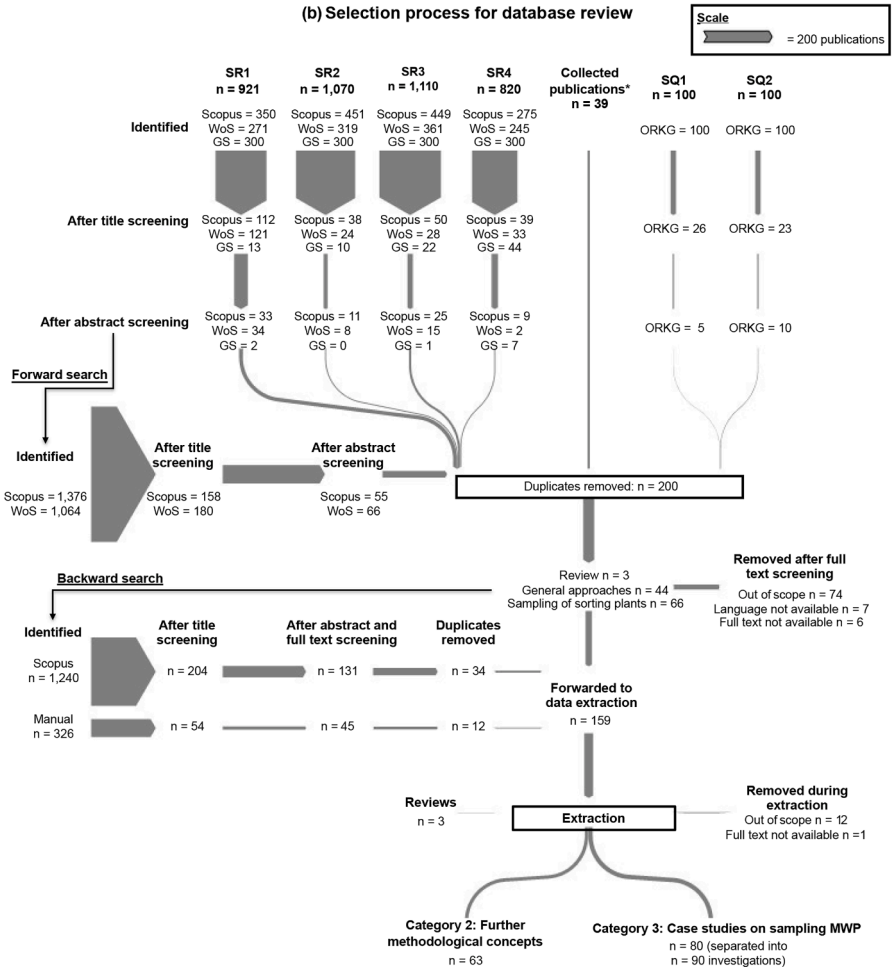


Fig. 2. Methodical approach for the database review conducted, with identified publications classified as Category 2 and 3. (a) search strings (SR) applied to Scopus, Web of Science (WoS), and Google Scholar (GS), and search questions (SQ) applied to ORKG Ask, and (b) the selection process of identified publications (* = publications collected by the authors prior to the review over 5 years).

inclusion was made between the previously defined three literature categories:

Category 1: Standards – Standards addressing MSW sampling were included. Additionally, standards that are part of a multi-standard series or closely linked to the identified MSW sampling standards (e.g., defining the manual analysis) were also included to provide a broader overview of existing standards.

Category 2: Further methodological concepts – Publications were included that address the sampling of MSW. Since the focus was on transferability to assess MWP, publications addressing methodological aspects of process sampling were included, as were those discussing relevant methods for determining the number of samples, defining sample size, and conducting manual analyses. These aspects had to be explicitly stated in the abstract.

Category 3: Sampling of MWP – Publications (case studies) were included that address the sampling and manual analysis of MWP (waste treatment/processing/sorting plants) for non-hazardous MSW. Only publications conducting manual waste composition analysis were included.

2.2.2. Exclusion criteria

During the scoping review, publications that address non-municipal or hazardous waste were excluded. Typical examples include publications on primary raw materials, defense-related waste, radioactive waste (e.g., from nuclear power plants or uranium processing facilities), pellets, residues from waste incineration or waste-to-energy plants, marine litter, waste from mineral landfills, or waste from industrial production processes. Furthermore, publications focusing on non-solid waste (e.g., oil, water, sewage sludge, effluents from wastewater treatment plants, and other forms of liquid waste) were excluded. The background was

that non-municipal, hazardous, and non-solid waste streams may impose different sampling requirements, and manual analyses are not feasible in some cases at all. Therefore, the focus is typically on preparing laboratory samples followed by laboratory-based analyses. Consequently, this type of sampling presents challenges distinct from those of manual analysis. To maintain a clear and manageable scope, the focus of this review was accordingly limited. In this context, publications that dealt exclusively with subsampling, laboratory-scale sample preparation methodologies, or chemical analyses were also excluded. Examples include publications on air pollution or bioaerosols (e.g., health risk assessments of waste sorting plants), chemical substances, methane potential, carbon footprint assessments, or compost quality. In addition, specific exclusion criteria were applied for each literature category:

Category 1: Standards – During the standards review, standards that had been withdrawn (e.g., due to updated versions) were considered during the secondary literature search but were excluded from the final selection to ensure the most current set of applicable standards.

Category 2: Further methodological concepts – Publications dealing with MSW sampling approaches were excluded if they merely applied a sampling guideline or a standard technique. However, a list of thereby additionally identified sampling guidelines (beyond those presented in Section 3.1) is provided in Supplementary material 1, also in languages other than German or English. Publications focusing on the collection, separation, or generation of household waste, or those primarily employing survey methodologies, were excluded because they were considered not to provide a direct contribution to the assessment of MWP. This encompasses evaluations of consumer behavior regarding waste collection, intentions to separate waste (in households), or the modeling and prediction of household waste generation.

Category 3: Sampling of MWP - Publications dealing with the sampling of MWP were excluded if they did not conduct manual analyses, only received samples from the sorting plant output without providing information about the sampling process, or used artificial samples that mimic the sorting plant output. Additionally, publications focusing on sensor-based approaches, machine learning, or plant modeling without validation through plant sampling and manual analyses were excluded. These exclusions were made to ensure consistency with the predefined scope (cf. Section 1) of analyzing the practical implementation of MWP sampling and manual analyses to describe the current state of practice.

2.2.3. Included and excluded publications

An overview of the selection process for the standards review is given in Fig. 1(b) and for the database review in Fig. 2(b).

During the **standards review**, a total of $n = 4{,}158$ publications were identified. In addition, $n = 279$ publications were identified during the backward search. After conducting title screening and removing duplicates, the full texts of $n = 192$ publications were assessed for eligibility. During the full-text screening, $n = 115$ publications were excluded as they were considered out of scope, and $n = 44$ were excluded as they were not available in English or German. Finally, a total of $n = 33$ standards have been included in the presented scoping review.

During the **database review**, a total of $n = 4{,}121$ publications were initially identified through search strings and queries applied to Scopus, Web of Science, Google Scholar, and ORKG Ask. While Google Scholar yielded $n = 43{,}808$ results, this number was not practically feasible to screen. ORKG Ask, similarly, imposes no result limit. However, since both platforms rank results by relevance, the screening was limited to the top 300 results from Google Scholar and the top 100 from ORKG Ask. These thresholds were defined at the point where no additional relevant literature had appeared for several consecutive publications. As the most relevant publications were found via Scopus and Web of Science, a forward search (i.e., screening publications that cited the initially selected publications) was conducted in both databases for all articles included after the abstract screening. The forward search yielded $n = 2440$ additional publications. After screening all publications and removing duplicates, $n = 200$ publications were retained for full-text screening. During the full-text screening, $n = 74$ publications were excluded as out of scope, $n = 7$ were excluded as they were not available in English or German, and $n = 6$ were excluded as the full texts were not accessible. The remaining $n = 113$ publications were subjected to a backward search (i.e., screening publications that were cited by the initially selected publications). For the $n = 97$ publications indexed in Scopus, secondary literature was extracted directly from Scopus. For the remaining $n = 16$ publications, a manual backward search was conducted. The backward search resulted in a total of $n = 1{,}566$ publications. After screening and removing duplicates, a final set of $n = 159$ publications was forwarded for data extraction. During data extraction, $n = 13$ publications were excluded (e.g., because different publications referred to the same investigation). The final number of publications from the database review considered in the scoping review was $n = 146$.

2.3. Data extraction

To extract data in alignment with the scoping review aim and the defined RQs, the identified publications (excluding $n = 3$ identified reviews) were categorized in three literature categories (deductive reasoning): *Category 1: Standards for MSW sampling* ($n = 33$), *Category 2: Further methodological concepts* ($n = 63$), and *Category 3: Case studies on sampling of MWP* ($n = 80$). The extraction criteria for each category are provided in Supplementary material 2. At least two people reviewed all extracted data. In cases of uncertainty or inconsistency, additional researchers reviewed the extracted data. In addition to the extracted data, bibliographic information was analyzed.

Publications assigned to *Category 3: Case studies on sampling of MWP* sometimes contained multiple independent full-scale sampling campaigns within one publication. To avoid potential bias arising from the combined release of several sampling campaigns in a single publication and to enable consistent data extraction, eight publications were divided into separate investigations during data extraction. Publications were only divided if full-scale sampling campaigns were separately methodologically described and evaluated (not if the same output stream from several sorting plants was sampled to compare the respective output streams). Thereby, a total of $n = 90$ investigations were extracted from Category 3 publications using defined criteria and forwarded to data analysis.

2.4. Collating, summarizing, and reporting the results

The data was primarily organized in Microsoft Excel. To visualize the resulting extracted data and bibliographic information, different visualization tools were used. Therefore, data was processed in Python using the Python packages pandas (The pandas development team, 2024) and numpy (Harris et al., 2020) for data structure and matplotlib (Hunter, 2007), seaborn (Waskom, 2021), networkX (Hagberg et al., 2008), geopandas (Bossche et al., 2024), and plotly (Plotly Technologies Inc., 2015) for graphic visualization.

2.5. Limitations

Despite the extensive effort invested in this scoping review, several limitations remain. First, the review focused exclusively on non-hazardous MSW, potentially excluding relevant studies on the sampling and manual analysis of hazardous or non-municipal waste. In addition, this review focuses on manual sample analysis. Although the creation of laboratory samples is mentioned in parts of the identified and included literature, the emphasis is clearly on the manual analysis of waste. The processes of comminution and size reduction for generating laboratory samples constitute an additional thematic field that is not comprehensively covered in this scoping review.

Methodological limitations exist due to resource constraints.

Publication selection was conducted by a single reviewer, increasing the risk of selection bias. The backward search used Scopus and may have excluded relevant gray literature. No independent parallel data extraction was conducted; instead, data were extracted by one individual, cross-checked by a second reviewer, and, in cases of uncertainty or inconsistency, reviewed by additional researchers. The applied approach aimed to achieve the most reliable results possible, while maintaining a reasonable balance between accuracy and practical feasibility. In addition, due to the field's heterogeneity in terminology, some literature clusters using alternative terms may not have been captured, despite multiple strategies to minimize bias. During the review, identified synonyms for relevant terms were collected and are listed in Supplementary material 3. The inclusion of gray literature presents a particular challenge. Although extensive efforts were undertaken, it remains possible that relevant gray literature was not identified. In addition, it should be emphasized that Google Scholar and ORKG Ask, which were primarily used to ensure the inclusion of relevant gray literature, pose challenges for reproducibility. Reproducibility remains limited for Google Scholar (Pozsgai et al., 2021) and for AI-based search processes, even when open-source code is available, as is the case for ORKG Ask.

Finally, it should be noted that a potential bias may arise from the language criteria applied. This scoping review considered publications in English and German. The principal reason is that the authors cannot ensure the level of linguistic proficiency needed to evaluate scientific content in other languages with methodological reliability. For reasons of transparency and good scientific practice, the authors refrained from relying on translations generated by language tools, including AI-based systems. Several additional standards and guidelines that were identified in languages other than German or English are provided in Supplementary material 1. However, these were not evaluated, and, given the nature of the literature selection, publications from Asian, South American, and Central American regions, as well as from several non-English-speaking African and European regions, may be underrepresented. The authors deliberately chose to include German-language publications and would like to encourage subsequent work to highlight relevant publications that were published in languages other than German or English to make them available to a broader public.

3. Results and discussion

During the conducted scoping review, three relevant literature reviews were identified. In 2008, Dahlén and Lagerkvist (2008) conducted a review of methods for household composition studies. In 1995, Scott (1995) gave an overview of sampling and analytical protocols related to MSW conversion to energy . And in 2015, Cimpan et al. (2015) reviewed literature on central (commingled) sorting and processing of recyclable materials contained in household waste. However, no overview of the sampling and manual analyses focusing on assessing MWP was found.

3.1. Category 1: Standards for municipal solid waste sampling (RQ1)

This section provides an overview of standards dealing with the sampling of MSW. The identified standards are given in Table 1. All standards presented in the first column of Table 1 address the actual sampling. Several of them are part of multi-standard series. The final column lists additional standards from these series that address, e.g., further sampling demands, manual analysis, data evaluation, and extended analytical procedures. This column also includes standards closely linked to the sampling standards, such as those describing subsequent sample preparation. Standards which are to the time of the review (February - June 2025) withdrawn (e.g., DIN EN 15442:2011-05 for the sampling of solid recovered fuels or OENORM 2123-3:2003-11 for the sampling of solid waste out of material streams) or which not focus explicitly on waste materials (e.g., DIN ISO 11648 for statistical aspects of sampling from bulk materials) were excluded.

Table 1 organizes the identified standards primarily by publisher and secondarily by year of publication. For ASTM standards, the chronological classification was based on the number immediately following the designation. This number indicates the year of acceptance (original adoption) or, in the case of a revision, the year of the last revision (cf. also (ASTM International, 2023)). For an assessment of the temporal development of the standards, reference is already made at this stage to the subsequent contextualization of all results (cf. Section 3.4.1, Fig. 7). The standard ASTM D 5321 was originally published in 1992. This standard addresses the manual composition analysis of unprocessed MSW and thus provides a foundation for a wide range of sampling objectives (ASTM D 5231-92, 1992 – Reapproved 2024-06-00). In 1998, ASTM D 6311 was published, with a particular focus on optimizing sampling design (ASTM D 6311-98, 1998 - Reapproved 2022-03-00). Between 2014 and 2021, several additional ASTM standards were revised, addressing different specific sampling contexts, such as sampling waste from pipes (ASTM D 5013-18, 2018-09-00), sampling waste piles (ASTM D 6009-19, 2019-09-00), and sampling unconsolidated waste from trucks (ASTM D 5658-20, 2020-12-00). The German guideline LAGA PN 98 was published in 2001, specifically addressing the sampling of solid and puncture-resistant waste for the assessment of suitability for material or energy recovery or for disposal (LAGA PN 98, 2001-12-00). However, LAGA PN 98 identifies MSW with particle sizes greater than 120 mm as a special case (LAGA PN 98, 2001–12–00). Between 2005 and 2011, the Austrian standard series OENORM S 2091 1-4 for the sorting analysis of solid waste was published. In addition to sampling procedures (OENORM S 2097-2, 2005-04-00), these standard series provide terminology (OENORM S 2097-1, 2005-04-00), requirements for manual sorting (OENORM S 2097-3, 2005-04-00), and guidance on the evaluation of results (OENORM S 2097-4, 2011-07-00). In 2006, DIN EN 14899 was published, establishing a general framework for the development of sampling plans, with a particular emphasis on preparing laboratory samples (DIN EN 14899, 2006-04-00). DIN EN 14899 makes reference to the CEN/TR 15310 series (CEN/TR 15310-1, 2006-11-00; CEN/TR 15310-2, 2006-11-00; CEN/TR 15310-3, 2006-11-00; CEN/TR 15310-4, 2006-11-00; CEN/TR 15310-5, 2006-11-00). However, as the responsible German standardization committee considered these technical reports to be insufficiently suitable for direct practical implementation, CEN/TR 15310 was published on European level via CEN (DIN EN 14899, 2006-04-00). In addition, CEN/TR 15310-1, states that, due to the high variability of waste types, sampling situations, and objectives, not all scenarios can be comprehensively covered (CEN/TR 15310-1, 2006-11-00). In subsequent years, increasing consideration was given to the variability of waste streams through the publication of guidelines addressing specific waste fractions, such as paper (DIN EN 17545, 2022-02-00; DIN EN 17085, 2019-08-00; INGEDE 14, 2009-04-00), plastics (DIN CEN/TS 16010, 2021-04-00; DIN CEN/TS 16011 (DIN SPEC 91011), 2013-04-00), and solid recovered fuel (SRF) (DIN EN ISO 21645, 2021-09-00).

Two standards were identified that explicitly address the sampling of treatment plants. OENORM S 2027-1 focuses on the sampling of waste from the MBT of MSW (OENORM S 2027-1, 2012-06-00). To determine the number of composite samples (qualified random samples), daily equivalents are calculated based on the plant's annual throughput (OENORM S 2027-1, 2012-06-00). The minimum individual sample size is estimated based on the 95th percentile of the maximum particle size, with each composite sample comprising at least ten individual samples (OENORM S 2027-1, 2012-06-00). The opening of the sampling device must be at least 2.5 times the maximum particle size (OENORM S 2027-1, 2012-06-00). However, OENORM S 2027-1 does not address waste fractions separated during mechanical treatment, such as rejected material, high-calorific fractions, or metals (OENORM S 2027-1, 2012-06-00). Instead, the standard emphasizes laboratory analysis of the collected samples, particularly the determination of stability parameters, which are defined in parts 2–4 of the associated standard series (OENORM S 2027-1, 2012-06-00; OENORM S 2027-2, 2012-06-00;

Table 1
Overview and extracted data from standards for MSW sampling identified through the standards review, classified as Category 1 publications (cf. Fig. 1).

Publisher	No., Year	Title	Material	Aim of the standard	Contains guidance on		Further parts of a multi-part or closely associated standard
					Sample size	Number of samples	
ASTM International	(ASTM D 5231-92, 1992 – Reapproved 2024-06-00)	Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste	Unprocessed MSW	Sampling and composition analyses of unprocessed municipal solid waste by manual sorting	x (fixed values)	x	
ASTM International	(ASTM D 6311-98, 1998 - Reapproved 2022-03-00)	Standard Guide for Generation of Environmental Data Related to Waste Management Activities: Selection and Optimization of Sampling Design	Waste	Sampling, waste characterization (incl. hot spot analyses) with a focus on sampling design optimization	x (general requirements)	x	
ASTM International	(ASTM D 4687-14, 2014 - Reapproved 2022-05-00)	Standard Guide for General Planning of Waste Sampling	Solid waste	Sampling at most common waste locations	Reference to ASTM E 122	x	
ASTM International	(ASTM D 5013-18, 2018-09-00)	Standard Practices for Sampling Wastes from Pipes and Other Point Discharges	Waste from flowing streams	Sampling at discharge points (moving waste streams)		x (general requirements)	
ASTM International	(ASTM D 6009-19, 2019-09-00)	Standard Guide for Sampling Waste Piles	Municipal waste	Sampling of waste piles (incl. hot spot analyses)		Reference to ASTM D 4687	
ASTM International	(ASTM D 5658-20, 2020-12-00)	Standard Practice for Sampling Unconsolidated Waste from Trucks	Unconsolidated solid wastes	Sampling of unconsolidated waste from vehicles		Reference to ASTM D 4687	
ASTM International	(ASTM D 6044-21, 2021-10-00)	Standard Guide for Representative Sampling for Management of Waste and Contaminated Media	Waste and contaminated media	Sampling from well-defined population with a focus on chemical analyses	x (general requirements)	x (general requirements)	
ASTM International	(ASTM D 5956-21, 2021-10-00)	Standard Guide for Sampling Strategies for Heterogeneous Wastes	Heterogenous waste	Introduction to statistical treatment of heterogeneous waste sampling issues and sampling strategies	x (general requirements)	x (general requirements)	
Austrian Standards International	(OENORM S 2097-2, 2005-04-00)	Sorting analysis of waste – Part 2: Sampling	Solid waste	Sampling for composition analyses	x (general requirements)	x	Further parts of OENORM S 2097 Sorting analysis of waste • (OENORM S 2097-1, 2005-04-00): Part 1: Concepts • (OENORM S 2097-3, 2005-04-00): Part 3: Sorting • (OENORM S 2097-4, 2011-07-00): Part 4: Evaluation of measuring results and analysis report
Austrian Standards International	(OENORM S 2027-1, 2012-06-00)	Evaluation of waste from mechanical-biological treatment – Part 1: Sampling	Waste from MBT plants	Sampling of MBT plants	x	x	Further parts of OENORM S 2027 Evaluation of waste from mechanical-biological treatment • (OENORM S 2027-2, 2012-06-00): Part 2: Stability parameters - Gas generation by incubation test • (OENORM S 2027-3, 2012-06-00): Part 3: Stability parameters - Gas generation by fermentation test • (OENORM S 2027-4, 2012-06-00): Part 4: Stability parameters - Respiration activity
Austrian Standards International	(OENORM S 2127, 2024-07-00)	Basic characterization of waste heaps or solid waste from containers and transport vehicles	Solid waste	Sampling of waste piles/ containers/vehicles	x	x	

(*continued on next page*)

Table 1 (*continued*)

Publisher	No., Year	Title	Material	Aim of the standard	Contains guidance on		Further parts of a multi-part or closely associated standard
					Sample size	Number of samples	
DIN – Institute for Standardization	(DIN EN 14899, 2006-04-00)	Characterization of waste – Sampling of waste materials – Framework for the preparation and application of a sampling plan	Waste	Sampling to generate laboratory samples	x (Reference to CEN/TR 15310-1 and general requirements)	x (Reference to CEN/TR 15310-1 and general requirements)	
DIN – Institute for Standardization	(DIN EN 17085, 2019-08-00)	Paper and board –Sampling procedures for paper and board for recycling	Recovered paper and board	Sampling of bulk or bales (sorting or drilling) from vehicles to test a delivery batch	x (fixed values)	x (fixed value)	(DIN EN 17545, 2022-02-00): Paper and board – Determination of composition of paper and board for recycling by gravimetric analysis
DIN – Institute for Standardization	(DIN CEN/TS 16010, 2021-04-00)	Plastics – Recycled plastics – Sampling procedures for testing plastics waste and recyclates	Plastic waste and recyclates	Sampling for quality control	x (and reference to DIN ISO 11648-2:2001)	x	(DIN CEN/TS 16011 (DIN SPEC 91011), 2013-04-00: Plastics - Recycled plastics - Sample preparation
DIN – Institute for Standardization	(DIN EN ISO 21645, 2021-09-00)	Solid recovered fuels – Methods for sampling	SRF	Sampling to support informed decisions regarding the subsequent handling and use of solid recovered fuels (SRF)	x	x (minimum fixed)	(DIN EN ISO 21646, 2022-09-00): Solid recovered fuels – Sample preparation
DIN – Institute for Standardization	(DIN SPEC 91466-1, 2024-01-00)	Packaging waste sorting plants –Efficiency in resource recovering and other quality features – Part 1: Measurement procedures and documentation	LWP	Sampling of materials stream and bales from LWP sorting plants	x (fixed values)	x (fixed values)	(DIN SPEC 91466-2, 2024-01-00): Packaging waste sorting plants – Efficiency in resource recovering and other quality features – Part 2: Certification
CEN - European Committee for Standardization	(CEN/TR 15310-1, 2006-11-00)	Characterization of waste - Sampling of waste materials - Part 1: Guidance on selection and application of criteria for sampling under various conditions	Waste	Statistical principles to sample waste population for basic characterisation, compliance testing or on-site verification.	x	x	Further parts of CEN/TR 15310 Characterization of waste - Sampling of waste materials • (CEN/TR 15310-2, 2006-11-00): Part 2: Guidance on sampling techniques • (CEN/TR 15310-3, 2006-11-00): Part 3: Guidance on procedures for sub-sampling in the field • (CEN/TR 15310-4, 2006-11-00): Part 4: Guidance on procedures for sample packaging, storage, preservation, transport and delivery • (CEN/TR 15310-5, 2006-11-00): Part 5: Guidance on the process of defining the sampling plan
INGEDE	(INGEDE 14, 2009-04-00)	Gravimetric Determination of Recovered Paper Composition	Recovered paper for deinking	Sampling to determine the composition of recovered paper for deinking	x (fixed values)	x (fixed values)	
LAGA – German Federal/ State Waste Working Group	(LAGA PN 98, 2001-12-00)	Guideline for the procedure of physical, chemical and biological investigations in connection with the recovery/disposal of wastes	Solid and puncture-resistant waste	Sampling from piles, bulk waste, containers, vehicles, and continuous waste streams (up to 120 mm particle size)	x	x	

OENORM S 2027-3, 2012-06-00; OENORM S 2027-4, 2012-06-00). The second identified standard addresses the sampling of (lightweight) packaging waste (LWP) sorting plants for plant certification (DIN SPEC 91466-1, 2024-01-00). It specifies one analysis per month for each output stream, based on a defined minimum sample size, which is the same for all output streams (DIN SPEC 91466-1, 2024-01-00). However, the standard primarily focuses on certification and currently holds the status of a preliminary standard (pre-standard) (DIN SPEC 91466-1, 2024-01-00). In conclusion, for standards focusing on plant sampling, OENORM S 2027 focuses on the sampling for assessing stability parameters, not manual compositions, and DIN SPEC 91466 holds the status of a preliminary norm, with only a short paragraph on the sampling and manual analyses. In addition to the two identified standards focusing on the sampling of specific waste sorting plants, several standards address the sampling from continuous material streams (e.g., (ASTM D 5013-18, 2018-09-00; LAGA PN 98, 2001–12–00; DIN EN ISO 21645, 2021-09-00; CEN/TR 15310-2, 2006-11-00)).

3.2. Category 2: Further methodological concepts (RQ1)

After identifying relevant standards for MSW sampling, this section focuses on general sampling approaches and provides additional

methodological considerations on the following focus areas. First, it outlines general aspects of determining the sample number, sample size (e.g., volume or mass per sample), and procedures for manual analysis, without specifically focusing on assessing MWP (Sections 3.2.1 – 3.2.3). Second, it presents literature on the sampling of compressed bales, often originating from MWP plants (Section 3.2.4), as well as considerations related to process assessment of MWP (Section 3.2.5). The aim is to provide an analysis for each of the defined focus areas, as these are considered particularly relevant for transferability to the assessment of MWP and are regarded as essential for the subsequent contextualization of the results. At this point, it should also be noted that methods in the waste management sector often depend strongly on the waste stream and objective of the investigation, particularly on the target parameters to be determined. Transferability to other target parameters or waste materials should be considered carefully in each case. For all publications identified under Category 2 (further methodological concepts), bibliographic data were analyzed and are presented in Supplementary material 4. Supplementary material 4 (b) displays the author networks for Category 2 publications, which are further grouped into four thematic focus areas (focus on (i) general sampling approaches, (ii) sampling of compressed waste, (iii) sampling of MWP, and (iv) the Theory of Sampling (TOS)). As general foundational references, the handbook on the topics of sampling and quality assurance, edited by Rasemann, was identified during the scoping review (Rasemann, 2005).

Publications that focus on the TOS primarily originate from the development of Gy's work (Gy, 2012, 2004a, 2004b, 2004c, 2004d, 1998, 1995, 1992, 1990, 1986, 1976; Gy and Marin, 1978). Although Gy's TOS primarily focuses on primary raw materials, its concepts have been partly applied to MSW, which is why the related publications are included here. For example, Dahlén and Lagerkvist (2008) discussed sampling errors in the TOS regarding (unprocessed) MSW sampling. However, it should be noted that TOS is often discussed in the context of preparing representative samples for subsequent chemical analysis (Petersen et al., 2005). Several comprehensive summaries of Pierre Gy's theory exist, and therefore, the whole theoretical framework is not repeated here. Gy himself published a four-part series on his work in 2004 (Gy, 2004a, 2004b, 2004c, 2004d). Petersen et al. (2005) compiled relevant aspects for the practical application of the TOS. Explanations on the different sampling errors and the definition of one-dimensional sampling can be found there (Petersen et al., 2005). One-dimensional sampling includes sampling process streams, e.g., from conveyor belts (Petersen et al., 2005). In this case, special attention must be paid to autocorrelated processes or product streams (Petersen et al., 2005). An accessible introduction to process sampling based on the TOS is given by Esbensen and Wagner (2017). For one-dimensional sampling, two additional sampling errors are introduced due to short- and long-range fluctuations (Petersen et al., 2005). The use of variograms as an analytical method to identify periodic trends is recommended (Petersen et al., 2005). Practical guidance on the application and interpretation of variograms is provided by Esbensen et al. (2007), who demonstrate that periodic patterns in the variogram can be highly informative about the dynamics of the underlying process and the structure of the one-dimensional data series. Khodier et al. (2020) used the TOS in combination with OENORM S2127 (from 2011) and the Danish Standard DS 3077 to develop a method for sampling and manually analyzing coarsely shredded commercial waste from a continuous stream. In addition, the authors evaluated the results with respect to the different sampling errors defined in the TOS (Khodier et al., 2020).

3.2.1. Number of samples for sampling municipal solid waste

Various methods for determining the number of samples, particularly for analyzing the composition of household waste, have been identified. In some cases, praxis-oriented approaches have been found. Brokaw and Hornberger developed a plant sampling approach in 1996, and took the number of incoming transporters as the number of samples (Brokaw and Hornberger, 1996). Frequently, a rearranged form of the margin of error (with finite element correction equal to one) and the standard deviation s (Lohr, 2019) (cf. Eq. (1)), or its normalized version using the coefficient of variation CV (cf. Eq. (2)), is employed to determine the required number of samples n (Pohlmann, 1994; Zwisele, 2005b, 1998). The parameter k represents the confidence coefficient, for which usually either the t-value of the t-distribution (for a defined number of degrees of freedom and a selected significance level), or the z-value of the standard normal distribution (for a selected significance level) is used (Zwisele, 2005b, 1998). ϵ, referred to e.g., as sampling precision or allowable random sampling error, is expressed either as an absolute deviation from the mean value when s is applied or as a relative deviation from the mean value when CV is used. Several standards incorporate variants of Eqs. (1) and (2) (ASTM D 4687-14, 2014 – Reapproved 2022-05-00; ASTM D 6311-98, 1998 - Reapproved 2022-03-00; ASTM D 5231-92, 1992 – Reapproved 2024-06-00; OENORM S 2097-2, 2005-04-00; LAGA PN 98, 2001-12-00).

$$n = \frac{(k^{*}s)^2}{\epsilon^2} \tag{1}$$

$$n = \frac{(k^{*}CV)^2}{\epsilon^2} \tag{2}$$

Zwisele (1998) adjusted the sample size according to Eq. (2) by applying a magnification factor to account for seasonal fluctuations. Martin et al. (1995) assumed their compositional data followed a multinomial distribution and transformed the component percentages using the arcsine square root transformation. The effect of different data transformations and distributions on the number of samples (and also the sample size) for solid waste sampling is also discussed by Lohani and Ko (1988). Sharma and McBean (2007) applied the approach described in Eq. (2) using the confidence coefficient of the standard normal distribution to determine the required number of samples during waste sampling and analysis. They observed that the coefficient of variation CV tends to stabilize as the number of samples n increases (Sharma and McBean, 2007). The proposed methodology was to continue sampling until the CV, and thereby the confidence interval of the mean, no longer changed significantly (Sharma and McBean, 2007). In 2008, Sharma and McBean developed a second methodology using Eq. (1), which utilizes the confidence coefficient of the t-distribution (Sharma and McBean, 2008). Their approach rearranges the formula to solve for the confidence coefficient t (Sharma and McBean, 2008). After each analyzed sample, the calculated confidence coefficient $t_{\text{calculated}}$ is compared against a critical value t_{critical} from t-distribution tables (Sharma and McBean, 2008). Once $t_{\text{calculated}} < t_{\text{critical}}$, no further samples are required (Sharma and McBean, 2008). However, both methodologies explicitly recommend collecting a minimum number of samples (5 – 10) before applying the respective termination criteria (Sharma and McBean, 2008, 2007). Another approach was employed by Mählitz et al. (2020) which used Eq. (2) and compared the resulting sample number using raw sampling data with the sample number calculated based on the CV derived from bootstrapped data. In addition, a non-parametric approach, likewise based on bootstrapping without any distributional assumptions, was applied to independently estimate the required number of samples (Mählitz et al., 2020). A cost-optimized method for determining the number of increments and composite samples was developed by Winterstein in 2012 (Winterstein, 2012). As a basis for this approach, Eq. (1) and a defined relationship between the variance of sampling and the variance of the analytical procedure were used (Winterstein, 2012). Considerations for cost-optimized sampling can also be found in (ASTM D 6311-98, 1998 - Reapproved 2022-03-00).

3.2.2. Sample size for sampling municipal solid waste

Several general guidelines and methodological approaches to determining sample size were identified. In their guide on the analysis of waste composition, Bidlingmaier and Müsken (2017) recommend using a sample size equivalent to 0.5 wt% of the weekly collected household

waste and comparable industrial waste from the area under investigation. Arnold and Born (2001) proposed a methodology to determine the sample size based on an estimated heterogeneity and the mean particle size. Also, Lagerkvist et al. (2011) stated that a sample size of a more homogeneous material may be smaller and Klee (1993) recommended in his approaches for estimation of solid waste quantity and composition to determine the sample size based on the characteristic particle size. Edirisinghe et al. (2023) proposed to use a sample volume of 1 m^3 (instead of a mass-related quantity) to analyze industrial mixed waste. Zwisele (2005b) stated in a publication on sampling methods that, due to the particle size distribution of output streams from heterogeneous coarse waste treatment processes (particles larger than 120 mm in diameter comprise more than 5 % of the total mass), increments with volumes of 20 to 60 liters are required. Regarding categories with small percentages, Sharma and McBean (2009) recommended a large mass per sample. Khodier et al. (2020) reached a similar conclusion. A relationship between the sample size and the sampling error was established based on the constant structural heterogeneity for different materials (Blottnitz, 1999; Blottnitz and Hoberg, 1998; Pehlken et al., 2000). Rasemann and Herbst (2000) developed a sampling model for heterogeneous materials to determine the sample size based on the distribution of grain and particle masses.

Based on the binomial distribution, Bunge and Bunge (1999) derived Eq. (3) for the minimal necessary sample mass M_{min} for monodisperse material systems, focusing on contaminated sites. The variable w represents the mass fraction of contaminant-bearing particles, while z corresponds to the confidence coefficient of the standard normal distribution for a selected significance level. The parameter ε describes the relative sampling error (sometimes also termed relative sampling precision/allowable random sampling error). ρ_c refers to the density of the contaminant-bearing particles. The variable $d_{c,\max}$ denotes the maximum particle size of the contaminant-bearing particles, whereas $d_{c,10\%}$ represents the maximum particle size of the smallest 10 % of the contaminant-bearing particles. (Bunge and Bunge, 1999; Skutan et al., 2005)

$$M_{\min} = \frac{1}{w} * \left(\frac{z}{\varepsilon}\right)^2 * \frac{\pi * \rho_C *}{6} \frac{1}{1 + 3 * \lg\left(\frac{d_{c,\max}}{d_{c,10\%}}\right)} * d_{c,\max}^3 \quad (3)$$

The approach proposed by Bunge and Bunge rests on several assumptions, e.g., that contaminant-bearing particles are randomly distributed in the bulk material, carry a uniform concentration of the target substance, and are perfectly spherical (Bunge and Bunge, 1999; Skutan et al., 2005). In addition, it was assumed that the surrounding matrix is free of the target substance (Bunge and Bunge, 1999; Skutan et al., 2005). Skutan et al. (2005) adapted Eq. (3) for MBT sampling by replacing particle diameter with particle mass since MBT outputs often lack a direct correlation between particle mass and diameter. Their approach also allowed multiple particle types, each contributing a defined fraction of the total contaminant load, to be considered simultaneously (Skutan et al., 2005). However, it should be noted that these approaches were applied to contaminant-bearing particles that usually occur at low concentrations within the total waste mass. Hennebert and Beggio (2021) found that 100 contaminant-bearing particles should be contained in a sample for a controlled degree of variability, a conclusion also reached by Bunge and Bunge (1999). Hennebert and Beggio also discuss this phenomenon based on size-concentration relationships in waste (Beggio and Hennebert, 2022).

3.2.3. Manual analysis

Before performing a manual analysis, sometimes quartering of waste is conducted. Terashima et al. (1984) compared random, stratified, and cluster sampling when performing quartering of waste. However, it should be noted that the quartering method is, for example, not recommended in Pitard's foundational work on the TOS (Pitard, 2019). For the actual manual analysis, specifications are given, e.g., in Büll (2006). For the manual analysis of packaging waste, special requirements were described by Velzen et al. (2018). The allocation of different waste groups is discussed in Bidlingmaier and Müsken (2017) and Büll (2006). Lagerkvist et al. (2011) stated that if more than a dozen categories are sorted, the sorting should be performed stepwise. Boer et al. (2018) identified factors affecting the reproducibility of the manual analyses of MSW. Reproducibility can be enhanced if the sorting equipment is standardized, the description of material fractions like organics and composites is provided, the depth of sorting (e.g., to separate packed food from its packaging) is defined, and the waste handling, before manual analyses, is documented (Boer et al., 2018). An overview of categories for manual analyses from different waste composition studies and regulations is given by Dahlén and Lagerkvist (2008).

3.2.4. Sampling of compacted waste

Sampling of compacted waste is a relevant approach for assessing MWP, as it includes bales commonly produced at the end of waste sorting and processing plants. The idea of compacting low-density, heterogeneous waste materials into a defined geometric form and then extracting an analytical sub-sample from the compacted body was developed in the mid-2000s (Kuyumcu and Zwisele, 2005, 2004; Zwisele, 2004). The basic concept is to compress a larger sample volume into a geometrically defined form (cube) (Kuyumcu and Zwisele, 2005; Zwisele, 2004). The cube is then successively divided until an analysis sample remains (Zwisele, 2004). This approach is also called the cube-dividing method (Kuyumcu and Zwisele, 2005). It has been shown that segregation effects due to differences in material density or the geometry and surface of particles are avoided, and as each division and selection step is precisely defined, subjective errors are largely excluded (Kuyumcu and Zwisele, 2005; Zwisele, 2004). However, Schade-Dannewitz et al. (2008) noted that the cube-dividing method has limited practical applicability, since the required effort for processing equipment (especially cutting) is immense, and many secondary-material systems cannot form a stable cube for cutting. Therefore, Schade-Dannewitz et al. developed 2008 the pressing-drill method, where the compressed waste (e.g., bales) is drilled for sample extraction (Schade-Dannewitz et al., 2008). Döring (2011) conducted mechanical technical development for practical field use and verified the method via a test series. Also, Tischberger-Aldrian et al. (2015) conducted two test series applying the pressing-drill method to a mid-calorific fraction derived from packaging waste. Wellacher et al. (2016) applied it to mixed plastic bales with added molybdenum foil, while potentially noting segregation effects during bale pressing. Borowski (2018) developed various procedures and drilling techniques for random volume sampling from bales, focusing on LWP and thereby supporting the standardization process for bale sampling. Another application for sampling compressed waste by drilling was described by Hartwell et al., who used a drilling approach (large-diameter borehole sampling method) to assess properties associated with the depth of MSW landfills (Hartwell et al., 2022, 2021). Sampling of compressed bales is currently applied, for example, in the quality assessment of recovered paper bales, where the procedure has been partially automated and is defined in (DIN EN 17085, 2019-08-00).

3.2.5. Sampling of mechanical waste processing operations

Different references discuss how representative sampling can be achieved from continuous material streams or conveyor belts. Gy and Marin (1978) identified four conditions for unbiased sampling from falling streams of particulate materials, which depend on the width of the cutter opening and the speed at which the cutter travels intermittently across the stream. Based on state-of-the-art practices for sampling mineral bulk materials and production-specific waste streams, Zwisele (2005b) recommended that samples should be taken preferably at transfer points along the conveyor, and each sample should cover the full cross-section of the belt. The reliability of conveyor belt sampling

largely depends on even material distribution (Zwisele, 2005a). For continuous streams, systematic random sampling is suggested, beginning after an appropriate lead time and proceeding at defined intervals (Zwisele, 2005b). Stange (1958) already discussed in 1958 that neighboring samples may exhibit correlated properties and that, therefore, sufficiently large intervals between samples are necessary. In addition, it should be assessed whether periodic fluctuations in material composition are to be expected, to minimize the risk of systematic sampling errors (Zwisele, 2005b). In practical plant operations, automated sampling devices are sometimes employed to reduce subjective influences (Hipke et al., 2004). The use of such systems was also recommended by Khodier et al. (2020), e.g., through the implementation of reversible conveyor belts, particularly to enable high increment sampling frequencies.

Examples of methodological considerations for sampling MWP are provided, for instance, by Prikler et al. (2013), who in 2013 compared different sampling strategies for refuse-derived fuels, including sampling from continuous material streams. They found that the sampling uncertainty is of the same order of magnitude as the analytical and sample preparation errors (Prikler et al., 2013). This is in contrast to other literature, where sampling uncertainty is typically estimated as higher (e.g., (Pehlken et al., 2005; Rasemann, 1993; Thomanetz, 1991)). Guidelines for evaluating waste management-related investigations depending on different sampling approaches, including an example from a waste treatment plant, are discussed in Zwisele (2008). Pehlken et al. (2005) examined in 2005 specific aspects of evaluating MWP, using the example of an eddy current separator. Also in 2005, Zwisele (2005a) discussed the determination of performance indicators for individual MWP. He suggested that, due to higher homogeneity, process sampling should preferably focus on the output streams (Zwisele, 2005a). As performance indicators, size reduction ratio, screen efficiency, recovery, yield (cf. also Section 3.3.3), and concentration/depletion efficiency were proposed (Zwisele, 2005a, 2005c).

Additionally, publications on methodological considerations for sampling entire sorting and processing plants were identified. For balancing mechanical-biological residual waste treatment plants, Skutan et al. (2005) used the method of substance flow analysis. They provided extensive guidance on statistical planning and evaluation methods, mainly to create samples for chemical analyses (Skutan et al., 2005). Pehlken et al. (2000) discussed several methodological aspects regarding the sampling of residual waste treatment plants. Samples of 100 liters were taken from the high calorific value product stream $>$ 60 mm (Pehlken et al., 2000). An increase in sample size to 200 liters did not result in significant changes in the observed ranges of variation (Pehlken et al., 2000). Due to fluctuations in moisture content, volume-based sampling was generally recommended (Pehlken et al., 2000). Feil et al. (2017) developed a decision tree to guide the sampling procedure in LWP sorting plants, providing procedural instructions and a framework for controlling the achievable accuracy during sampling. Relevant criteria for proper plant sampling include, e.g., constant process parameters, uniform material distribution in the plant, and available sampling access points (Feil et al., 2017).

3.3. Category 3: Sampling of mechanical waste processing (RQ2)

After discussing the identified methodological approaches, this section summarizes publications that include practical case studies of MWP sampling, thereby providing an overview of the current state of the art in this field. Fig. 3(a) provides an overview of the identified publications categorized by the type of waste stream examined. If a publication encompasses multiple investigations (cf. Section 2.3) addressing different waste streams, it is listed multiple times. The waste streams are categorized according to several overarching terms. The term SC MSW includes plastics, LWP, paper and board, and single or commingled streams. Residual MSW (rMSW) is also referred to as refused MSW (Ranieri et al., 2017), or residual household waste (Aranda Usón et al., 2012) (for more synonyms cf. Supplementary material 3). It appears that rMSW and MSW are sometimes used synonymously. However, depending on the existing waste collection system, MSW may also represent the only waste stream collected, thereby encompassing a broad range of materials. The relatively low number of publications on biowaste (organic fraction of MSW/source-separated biowaste) and construction and demolition waste (CDW) can be explained by the fact that plant sampling described in the literature for these streams often lacks manual analysis at the article level and is thus not included in this scoping review (cf. Section 2.2). The author's network, illustrated in Fig. 3(b), shows that most research networks are relatively small and typically focus on specific waste streams. Author networks (1) and (2) are detailed in Fig. 3(c) and (d), respectively. The network in Fig. 3(c) represents a research group from Great Britain, while the network in Fig. 3(d) includes researchers from Germany, Austria, and the Netherlands. Research network (2) is also the largest identified network in the dataset. Overall, the dataset suggests that previous research on sampling for assessing MWP has involved limited collaboration and has primarily occurred within isolated networks.

3.3.1. Dataset description and investigated plants

The number of publications published per year for the sampling of MWP is given in Fig. 4(a). Until 2007, there were almost no publications on the sampling and manual analyses of MWP. Starting in 2012, the frequency of publications increased. Fig. 4(b) illustrates the countries in which the studies were conducted or, if not explicitly stated, where the research was published. Most publications originated from Europe, with Spain, Italy, Austria, and Germany being particularly represented, which might also be due to the language restrictions (cf. Section 2.5). Fig. 4(c) shows the types of investigated waste processing and sorting plants categorized by waste streams. The most frequently investigated plant type is the material recovery facility (MRF). The term MRF represents a general term for waste processing and sorting plants, as evident from the various types of waste streams that are treated by MRFs. Identified terminologies for MRF are, e.g., solid waste sorting plant (Al-Athamin et al., 2021), MSW processing facility (Ashkiki et al., 2019), mechanical treatment plant (Cesaro and Belgiorno, 2020; Phyu et al., 2024), LWP sorting facility/plant (Picuno et al., 2021; Spies et al., 2024) or SRF/refuse-derived fuel (RDF) production plant/process (Curtis and Sarc, 2021; Nasrullah et al., 2015, 2014a, 2014b; Sarc et al., 2020) (cf. also Supplementary material 3). Plants categorized as mechanical-biological or biological-mechanical treatment (MBT/BMT) plants include a biological stage for treating organic waste. MBT/BMT are the second-most frequently referenced plant types in the investigated dataset. In contrast to MRF and MBT/BMT, which treat a wider range of waste streams, specialized facilities, such as waste of electrical and electronic equipment (WEEE) or CDW sorting plants, typically process only their designated waste streams.

Fig. 4(d) - (f) shows the throughput of the investigated plants. If multiple values were reported, the throughput measured during the actual trial was plotted; if both theoretical capacity and actual throughput were provided, the actual throughput was plotted; and if several throughputs were reported (e.g., for different time periods or plants), the mean throughput was plotted. For publications providing sufficient data (e.g., operating hours per day or operating days per year), unit conversions were performed, which may result in a single plant appearing multiple times in the plots. However, in the absence of such details, unit conversion across the plots is not feasible. For MBT/BMT plants, throughput is mostly reported on an annual basis, likely because the extended duration of biological stages makes daily or hourly data less significant. Throughput values showed considerable variation, likely due to differences in operating days per year or month, or operating hours per day. Except for one MRF and two MBT/BMTs, all reported hourly throughputs were below 30 t/h.

3.3.2. Sampling goals and characteristics

Criteria related to the actual sampling procedures of MWP were extracted to provide insight into the current state of sampling practice. Due to heterogeneous terminology and occasionally limited methodological descriptions, data extraction for these criteria was particularly challenging. Fig. 5(a) presents the identified sampling goals and their corresponding proportions among the publications. The publications were assigned to specific sampling goals based on the stated research objective. However, there is often a combination of several sampling goals. For example, when testing a recycling process, a specific output stream (product or reject) is typically assessed as well.

The most frequent sampling goal was the performance assessment of the investigated plant, followed by sampling to generate data for or validate a model or method, and the assessment of a specific output stream (no product). In the latter case, researchers often examined whether a rejected stream could be classified or used as RDF or SRF. Fig. 5(b) shows the number of publications that sampled input and/or output/internal streams. Streams that were sampled but not manually analyzed were also considered. Over half of the reviewed publications focused on sampling output or internal process streams. Approximately one-third included sampling of both input and output/internal streams. In investigations where quantitative information was provided, the number of input samples typically ranged from 1 to 20 (cf. Fig. 5(c)). The weight of most input samples ranged between 101 kg and 1000 kg per sample. As illustrated in Fig. 5(d), many publications reported sampling multiple output streams (this includes cases in which the same stream was sampled at different plants). Supplementary material 5 provides a comparison of sampling goals and the sampled output streams, indicating that the underlying sampling goal influences the selection of material streams. Overall, more samples were typically collected from the output/internal streams than from the input, possibly to account for variability across different process points (compare Fig. 5(c) and (e)). This observation is also consistent with Fig. 5(e), which indicates that more samples were generally taken when multiple output and/or internal streams were sampled.

For publications on MWP sampling, only a limited number of approaches and guidelines were identified for determining the number of samples or the required sample size. Some publications state that the number of samples should be adjusted based on the amount per sampled output stream (Blasenbauer et al., 2024; Feil et al., 2016; Spies et al., 2024; Tanguay-Rioux et al., 2022). López et al. (2018) used the German Guideline LAGA PN 98, which recommends a certain sample number per sampled volume (LAGA PN 98, 2001-12-00). Alessi et al. 2020 referenced OENORM S 2027-1, 2012-06-00, which states that at least 10 individual samples (increments) shall be taken. To determine the required individual sample size M in kg, several studies referenced Eq. (4) (Alessi et al., 2020; Feil et al., 2016; López et al., 2018), which relates the mass to the particle size PS of the sampled stream in mm. PS can be defined as the maximum particle size of the 95th percentile of the material (Alessi et al., 2020; OENORM S 2027-1, 2012-06-00) or the maximum particle size (LAGA PN 2/78K, 1983-12-00; Feil et al., 2016; López et al. 2018). Moura et al. (2018) calculated the sample size using the tolerable sampling error and the population size. In addition, multiple authors emphasized that smaller particle sizes require smaller sample sizes (Jansen et al., 2013; Montejo et al., 2013). Ashkiki et al. 2019 referenced ASTM D 5231-92, 1992 – Reapproved 2024-06-00 and adapted their sample sizes based on the assumption that a waste stream after sieving is less heterogeneous than unprocessed waste. In roughly one-fifth of all investigations, it was stated that increments were collected and later combined into composite samples. However, the distinction between individual and composite samples was sometimes difficult to infer from the available information.

$$M = 0.06^{*}\ PS \tag{4}$$

For actual sample extraction, several publications took samples directly from the running streams (falling material streams or conveyor belts) (e.g., (Blasenbauer et al., 2024; Cook et al., 2015; Curtis and Sarc, 2021; Feil et al., 2016; Maris et al., 2015; Möllnitz et al., 2021; Tanguay-Rioux et al., 2022)). It was stated that sampling from a running stream is preferable over sampling from a static lot or bulk (Feil et al., 2016). For the sampling of material streams (falling, stationary, or moving material) OENORM S 2123–3 was referenced (Möllnitz et al., 2021). Other sample extraction strategies included the sampling of bales (Gallardo et al., 2014; Mastellone et al., 2017; Tanguay-Rioux et al., 2022), trucks (Mastellone et al., 2017; Pera et al., 2023), containers (Adrados et al., 2013), or from static bulks/lots (Bernat et al., 2021; Montejo et al., 2010). To reduce the sample size, samples taken were often quartered (e.g., (Edo-Alcón et al., 2016; Gallardo et al., 2014; Jedrczak et al., 2023; Mastellone et al., 2017; Montejo et al., 2013, 2011, 2010; Moura et al., 2018; Sbrolini Tiburcio et al., 2021)).

In addition, some publications referenced further guidelines or standards, e.g., the Methodology for the Analysis of Solid Waste (SWA Tool) (Al-Athamin et al., 2021; Aranda Usón et al., 2012; Moura et al., 2018), the French procedure MODECOM™ (Araújo Morais et al., 2008; Bayard et al., 2018, 2010; Correa et al., 2022; Mondelli et al., 2022; Montejo et al., 2013, 2011, 2010), the ASTM standard D 5231 (Ashkiki et al., 2019; Phyu et al., 2024), the Polish standard PN-Z-15006:1993P (Bernat et al., 2021), the technical standard UNI 10802:2013 (Cesaro and Belgiorno, 2020), or the Brazilian standard ABNT NBR 10007:2004 (Correa et al., 2022; Mondelli et al., 2022; Oliveira et al., 2025; Sbrolini Tiburcio et al., 2021). However, the use of standards was often focused on input sampling or emphasized manual analysis. Regarding SRF analyses, DIN standard 15359 (Edo-Alcón et al., 2016), DIN standard 15442 (methods for sampling) (Brás et al., 2020, 2017; Nasrullah et al., 2015, 2014a, 2014b; Ranieri et al., 2017), and DIN standard 15443 (methods for the preparation of the laboratory sample) (Brás et al., 2020, 2017) were referenced.

3.3.3. Determined parameters, process indicators, and evaluation of the results

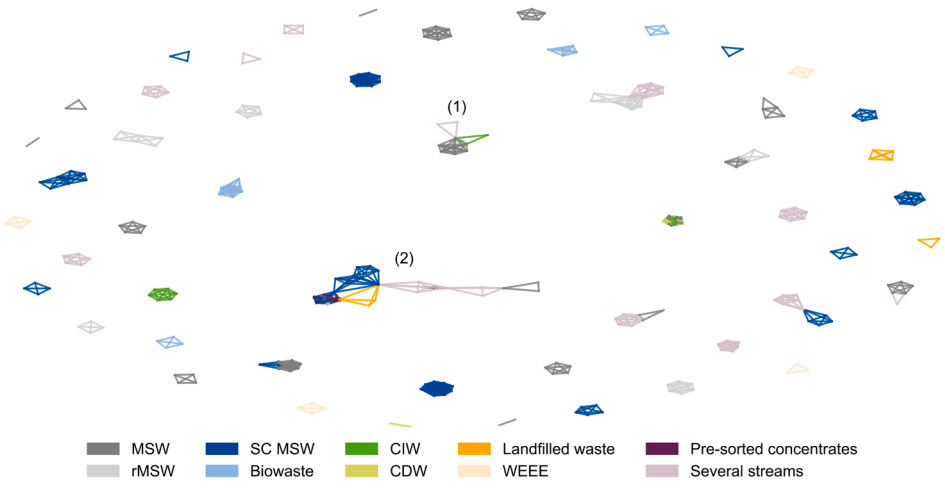
Each publication included a manual analysis of at least one sample (cf. Section 2.2). The number of categories analyzed is presented in Fig. 6(a). When multiple manual analyses were conducted, the maximum number of analyzed categories was extracted. Most studies (i.e., those whose whiskers lie within the 1.5 inter-quartile range) differentiated between 2 and 25 categories. Additional determined parameters are shown in Fig. 6 (b), with stacked bars indicating the waste streams processed in the analyzed plants (calorific value includes higher/lower heating values and gross/net calorific values). The left bar shows the overall distribution of waste streams across all investigations for comparison. It is evident that, particularly for SC MSW, parameters beyond manual composition were rarely determined. This may be attributed to the generally high sampling effort for SC MSW, as SC waste sorting plants typically produce numerous output streams, making comprehensive sampling more demanding. Moreover, for product streams such as compost or SRF/RDF (derived from MSW, rMSW, or biowaste), additional parameters are more frequently determined (often due to requirements set by corresponding standards).

Based on the manual compositions, different process indicators can be derived. Purity P (Eq. (5)) or concentration c_i (Eq. (6)) was considered determined when the mass of an individual material category m_i was divided by the total mass m. Purity is defined as the concentration of a target material P. Since it was not always possible to clearly determine when a material was classified as a target material, both indicators were recorded together. Recovery was considered determined if a total output stream mass m_{out} was divided by the total input mass m_{in} according to Eq. (7). For the yield Y (material-specific recovery), in addition to the classical definition given in Eq. (8) with the mass of material i in the output stream $m_{i,out}$ and the mass of material i in the input $m_{i,in}$, two alternative calculation approaches were identified. In these, either the entire output stream m_{out} was treated as material i, assuming 100 % purity (cf. Eq. (9)), or the mass of material i in the output $m_{i,out}$ was divided by the total input mass m_{in} (cf. Eq. (10)). These approaches were

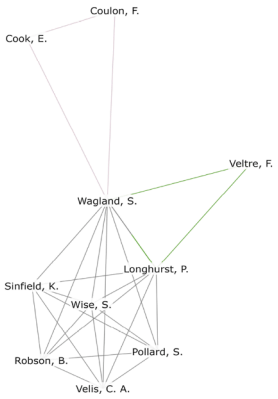
(a) Included publications and investigated material streams

Waste stream	Publications
MSW	(Ariņa et al., 2020; Ashkiki et al., 2019; Bilitewski et al., 1985; Brás et al., 2020; Cesaro and Belgiorno, 2020; Chang and Chang, 1996; Dias et al., 2014; Dias et al., 2012; Elrabaya, 2021; Gallardo et al., 2014; Ham et al., 2020; López-Delgado et al., 2005; Mondelli et al., 2022; Montejo et al., 2011; Montejo et al., 2010; Nasrullah et al., 2015; Oliveira et al., 2021; Sbrolini Tiburcio et al., 2021; Velis et al., 2013; Zwisele and Böhm, 2013)
rMSW	(Aranda Usón et al., 2012; Araújo Morais et al., 2008; Bayard et al., 2018; Bayard et al., 2010; Bernat et al., 2021; Jansen et al., 2013; Lieto et al., 2019; Lombardi et al., 2022; Montejo et al., 2013; Ranieri et al., 2017)
SC MSW	(Adrados et al., 2013; Bárkányi et al., 2022; Boz Noyan et al., 2022; Correa et al., 2022; Damgacioglu et al., 2020; Eule, 2013; Feil et al., 2016; Ip et al., 2018; Kleinhans et al., 2021; Kroell et al., 2024; Marco et al., 2009; Moura et al., 2018; Picuno et al., 2021; Prochazka et al., 2024; Shalitha Perera et al., 2025; Spies et al., 2024; Tanguay-Rioux et al., 2022; Tanguay-Rioux et al., 2021)
Biowaste	(Alessi et al., 2020; Badini et al., 2023; Carmo Precci Lopes et al., 2019; Hansen et al., 2007b; Hansen et al., 2007a; Pognani et al., 2012)
CIW	(Al-Athamin et al., 2021; Curtis and Sarc, 2021; Nasrullah et al., 2014a; Wagland et al., 2012)
CDW	(Brunner and Stämpfli, 1993; Nasrullah et al., 2014b)
Landfilled waste	(Kaartinen et al., 2013; López et al., 2018; Phyu et al., 2024)
WEEE	(Kim et al., 2014; Maris et al., 2015; Martinho et al., 2012; Menad et al., 2013)
Pre-sorted concentrates	(Curtis and Sarc, 2021; Feil et al., 2016)
Several streams	(Blasenbauer et al., 2024; Bobek-Nagy et al., 2023; Brás et al., 2017; Cook et al., 2015; Edo-Alcón et al., 2016; Ferronato et al., 2022; Jedrczak et al., 2023; Mastellone et al., 2017; Möllnitz et al., 2021; Oliveira et al., 2025; Pera et al., 2023; Ramos Casado et al., 2016; Sarc et al., 2020)

(b) Author network by waste stream



(c) Detailed author network (1)



(d) Detailed author network (2)

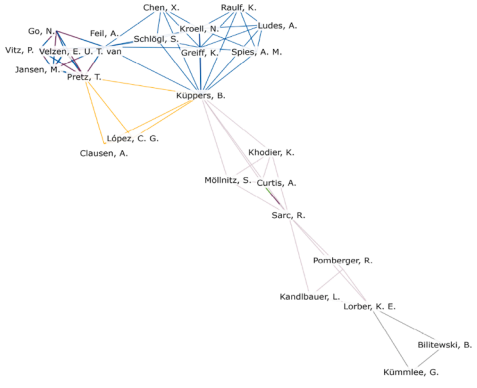


Fig. 3. Data extracted from investigations (case studies) addressing the practical application of sampling and manual analysis to assess MWP, identified through the database review, classified as Category 3 publications (cf. Fig. 2). A contextualization for the identified investigations is presented, including (a) all Category 3 investigations categorized per material stream, (b) author networks of all Category 3 investigations (please note that single-author publications are omitted, as they produce no co-authorship links), and (c) – (d) detailed views of selected author networks (Please refer to the following references for (a): (Adrados et al., 2013; Al-Athamin et al., 2021; Alessi et al., 2020; Aranda Usón et al., 2012; Araújo Morais et al., 2008; Ariņa et al., 2020; Ashkiki et al., 2019; Badini et al., 2023; Bárkányi et al., 2022; Bayard et al., 2018; Bayard et al., 2010; Bernat et al., 2021; Bilitewski et al., 1985; Blasenbauer et al., 2024; Bobek-Nagy et al., 2023; Boz Noyan et al., 2022; Brás et al., 2020, 2017; Brunner and Stämpfli, 1993; Carmo Precci Lopes et al., 2019; Cesaro and Belgiorno, 2020; Chang and Chang, 1996; Cook et al., 2015; Correa et al., 2022; Curtis and Sarc, 2021; Damgacioglu et al., 2020; Dias et al., 2012, 2014; Edo-Alcón et al., 2016; Elrabaya, 2021; Eule, 2013; Feil et al., 2016; Ferronato et al., 2022; Gallardo et al., 2014; Ham et al., 2020; Hansen et al., 2007a, 2007b; Ip et al., 2018; Jansen et al., 2013; Jedrczak et al., 2023; Kaartinen et al., 2013; Kim et al., 2014; Kleinhans et al., 2021; Kroell et al., 2024; Lieto et al., 2019; Lombardi et al., 2022; López et al., 2018; López-Delgado et al., 2005; Marco et al., 2009; Maris et al., 2015; Martinho et al., 2012; Mastellone et al., 2017; Menad et al., 2013; Möllnitz et al., 2021; Mondelli et al., 2022; Montejo et al., 2013, 2011, 2010; Moura et al., 2018; Nasrullah et al., 2015, 2014a, 2014b; Oliveira et al., 2025; Oliveira et al., 2021; Pera et al., 2023; Phyu et al., 2024; Picuno et al., 2021; Pognani et al., 2012; Prochazka et al., 2024; Ramos Casado et al., 2016; Ranieri et al., 2017; Sarc et al., 2020; Sbrolini Tiburcio et al., 2021; Shalitha Perera et al., 2025; Spies et al., 2024; Tanguay-Rioux et al., 2022; Tanguay-Rioux et al., 2021; Velis et al., 2013; Wagland et al., 2012; Zwisele and Böhm, 2013).

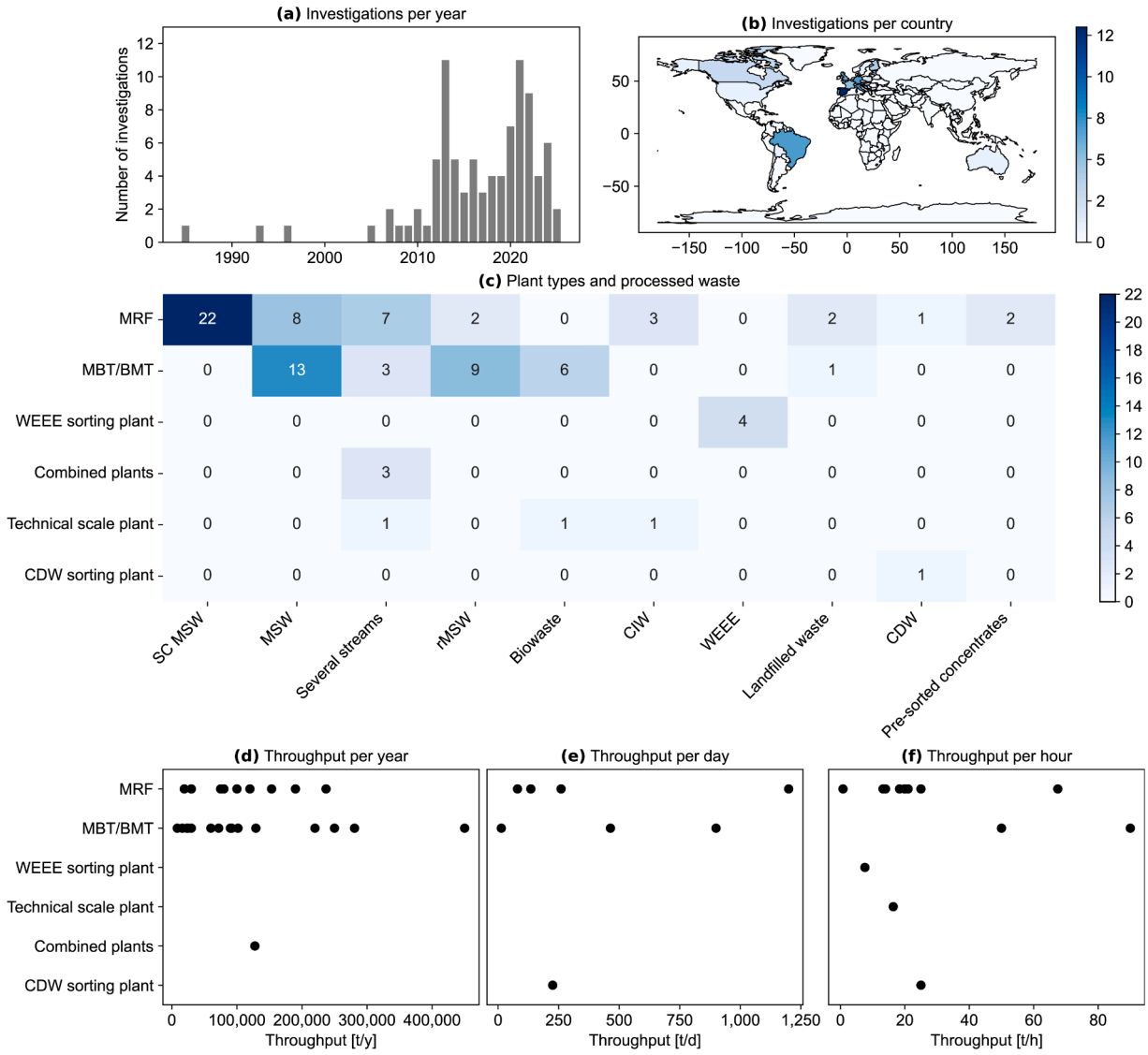


Fig. 4. Data extracted from investigations (case studies) addressing the practical application of sampling and manual analysis to assess MWP, identified through the database review, classified as Category 3 publications (cf. Fig. 2). This figure presents an overview of the datasets from Category 3 investigations, intended to support more accurate contextualization of the results. This includes (a) the number of investigations per year, (b) the number of investigations by country, (c) the number of investigations per waste stream in relation to the investigated plant type, and (d) – (f) throughput characteristics of the plants examined in the identified investigations (data included where available in the identified investigations).

often applied when only input or output streams were manually analyzed. In addition, Jansen et al. (2013) proposed a further distinction between gross and net recovery/yield, whereby gross indicators include non-recyclable fractions in the numerator, while net recovery excludes them. Overall, the authors would like to emphasize that terminology varied considerably across the reviewed literature. In the absence of clearly defined equations, it was often difficult to determine which indicators were calculated. This issue was especially pronounced for yield indicators, where a wide range of terms and definitions is used (cf. also Supplementary material 3). A clear definition of process indicators would significantly enhance the transparency and usability of waste-management-related data for the assessment of MWP. A first approach and suggestions for harmonized terminology are given in Supplementary material 3.

$$\text{Purity } P = \frac{m_P}{m} \tag{5}$$

$$\text{Concentration } c_i = \frac{m_i}{m} \tag{6}$$

$$\text{Recovery } R = \frac{m_{out}}{m_{in}} \tag{7}$$

$$\text{Yield } Y_i = \frac{m_{i,out}}{m_{i,in}} \tag{8}$$

$$\text{Yield input analyzed } Y_{Input,i} = \frac{m_{out}}{m_{i,in}} \tag{9}$$

$$\text{Yield output analyzed } Y_{Output,i} = \frac{m_{i,out}}{m_{in}} \tag{10}$$

The number of investigations that determined the indicators purity/concentration, recovery, and yield is shown in Fig. 6(c). Most of the included investigations determined purities/concentrations. Less than half of the investigations reported recovery. An even smaller portion of investigations determined yields, which may be attributed to the relatively high sampling effort required (typically involving sampling of input and output streams or all output streams). Fig. 6(d) shows the proportion of process indicators categorized by the waste streams

(a) Identified sampling goals

Sampling goal	Description	Percentage of investigations
Performance assessment - plant	Assessing the performance of an investigated plant e.g., to determine process efficiencies, enable process optimization or show correlation between material characteristics and plant equipment.	24.4%
Performance assessment - treatment step	Assessing the performance of specific treatment steps e.g., to determine the efficiency of a specific treatment step, quantify the influence of different machine parameters or compare different aggregates.	7.8%
Assessment of specific output stream (no product)	Assessing a specific output stream (reject) e.g., to obtain data regarding its composition and other pertinent parameters, determine its suitability for utilization as RDF/SRF or to analyze its potential use in a specific recycling process.	17.8%
Assessment of product stream	Assessing a product stream e.g., to analyze the product quality or compare product qualities from different plants.	6.7%
Input assessment	Assessing a plant's input material e.g., to obtain data regarding its composition and other pertinent parameters, to test operating modifications to respond to variations of MSW compositions or to determine its influence on sorting efficiencies and output streams.	6.7%
Gain data for model or validate model/method	Obtain data for model application or validate a model or method (e.g., a sampling technique, sensor-based approach) using realistic data.	17.8%
Determine recovery potential of specific material	Assess the recovery potential of a specific material or material type.	10.0%
Check potential to process specific waste in plant	Assess whether an existing plant is suitable for processing a waste stream that has not previously been treated.	3.3%
To test recycling process	Sampling of a specific output stream for integration in a recycling process e.g., to evaluate different recycling process parameters or to determine the influence of material composition and impurity contents.	5.6%

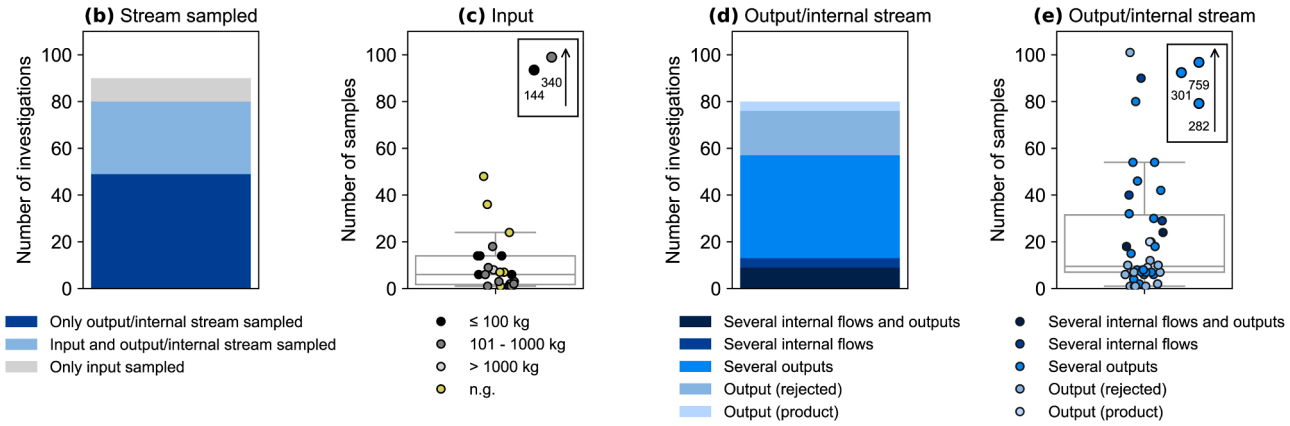


Fig. 5. Data extracted from investigations (case studies) addressing the practical application of sampling and manual analysis to assess MWP, identified through the database review, classified as Category 3 publications (cf. Fig. 2). Depicted are key practical aspects of MWP sampling, including (a) sampling goals, (b) the material streams sampled (input/output), (c) the number of input samples collected, (d) the types of output or internal streams sampled, and (e) the number of samples taken per output or internal stream (data included where available in the identfied investigations).

processed in the investigated plants (for output streams, no distinction was made regarding whether input was also sampled). It can be observed that recoveries and yields were disproportionately often determined when multiple output streams were sampled.

In addition to the discussed process indicators, several other process indicators were identified during the literature review. Mastellone et al. (2017) proposed indicators for efficiency evaluation, particularly concerning target parameters (e.g., processed input relative to target processed input, recovery relative to target recovery, and plant operating time relative to target plant operating time). Economic indicators were frequently calculated, such as the net present worth (NPW) (Al-Athamin et al., 2021), the return on investment (ROI) (Al-Athamin et al., 2021), and the sales revenues (Elrabaya, 2021). Additionally, broader economic assessments (Prochazka et al., 2024) and cost-benefit analyses (Shalitha Perera et al., 2025) were conducted. Moreover, publications often calculated mass balances or conducted material flow analyses (Alessi et al., 2020; Araújo Morais et al., 2008; Bayard et al., 2010; Blasenbauer et al., 2024; Damgacioglu et al., 2020; Picuno et al., 2021; Pognani et al., 2012). In some cases, energy balances were calculated (Nasrullah et al., 2015, 2014a, 2014b; Phyu et al., 2024). When residual fractions were landfilled, indicators such as the energy potential going to landfill (Aranda Usón et al., 2012) or the (recyclable) material going to landfill (Pera et al., 2023) were determined. Moreover, indicators for specific mechanical operations were used, such as the liberation degree for comminution (Kim et al., 2014; Menad et al., 2013) or the screening efficiency for sieving (Möllnitz et al., 2021). In addition to determining process indicators, other criteria were occasionally investigated. The most examined criteria included seasonal variations, multiple criteria, and different input materials (cf. Fig. 6(e)). The most frequently used methods to evaluate the manual analysis results are presented in Fig. 6 (f). However, extensive evaluations of manual sampling results for MWP were rarely conducted. In conclusion, the determined sampling characteristics, methods, and evaluated parameters showed a wide range within the reviewed investigations on MWP sampling and manual analyses.

3.4. *Contextualization and implications (RQ3)*

In summary, a broad literature base was gathered on sampling and manual analyses of MSW, with a focus on MWP assessment. This section collates and contextualizes the identified evidence and aims to derive implications for the development of methods to assess MWP. An overview of the time evolution of the literature across all three categories (cf. Sections 3.1, 3.2, and 3.3) is shown in Fig. 7.

3.4.1. *Contextualization of identified literature*

About half of the standards (Category 1, cf. Section 3.1) originate from the period before 2012, with the rest published subsequently. Many standards focus on sampling household waste before mechanical treatment. This may be because sampling efforts often focus on waste

collection to estimate, e.g., the potential for improved source separation by consumers or the amounts of contained secondary resources in the collected waste streams. In contrast, sampling of continuous process streams remains a topic of secondary relevance. Although mentioned in different standards, it is not comprehensively addressed in dedicated standards for different waste material streams. Exceptions are OENORM S 2027-1, 2012-06-00, although its primary focus is on the analysis of the biological fraction and related parameters, i.e., the focus lies not on manual but instead on laboratory analyses (OENORM S 2027-2, 2012-06-00; OENORM S 2027-3, 2012-06-00; OENORM S 2027-4, 2012-06-00) and DIN SPEC 91466-1, 2024-01-00, which is only a preliminary standard. At the same time, the mechanical processing and sorting of different waste materials, particularly in Europe, is currently being driven by various political initiatives such as the Packaging and Packaging Waste Regulation 2025/40 (PPWR) (The European Parliament and the Council of the European Union, 2025b) and the revision of

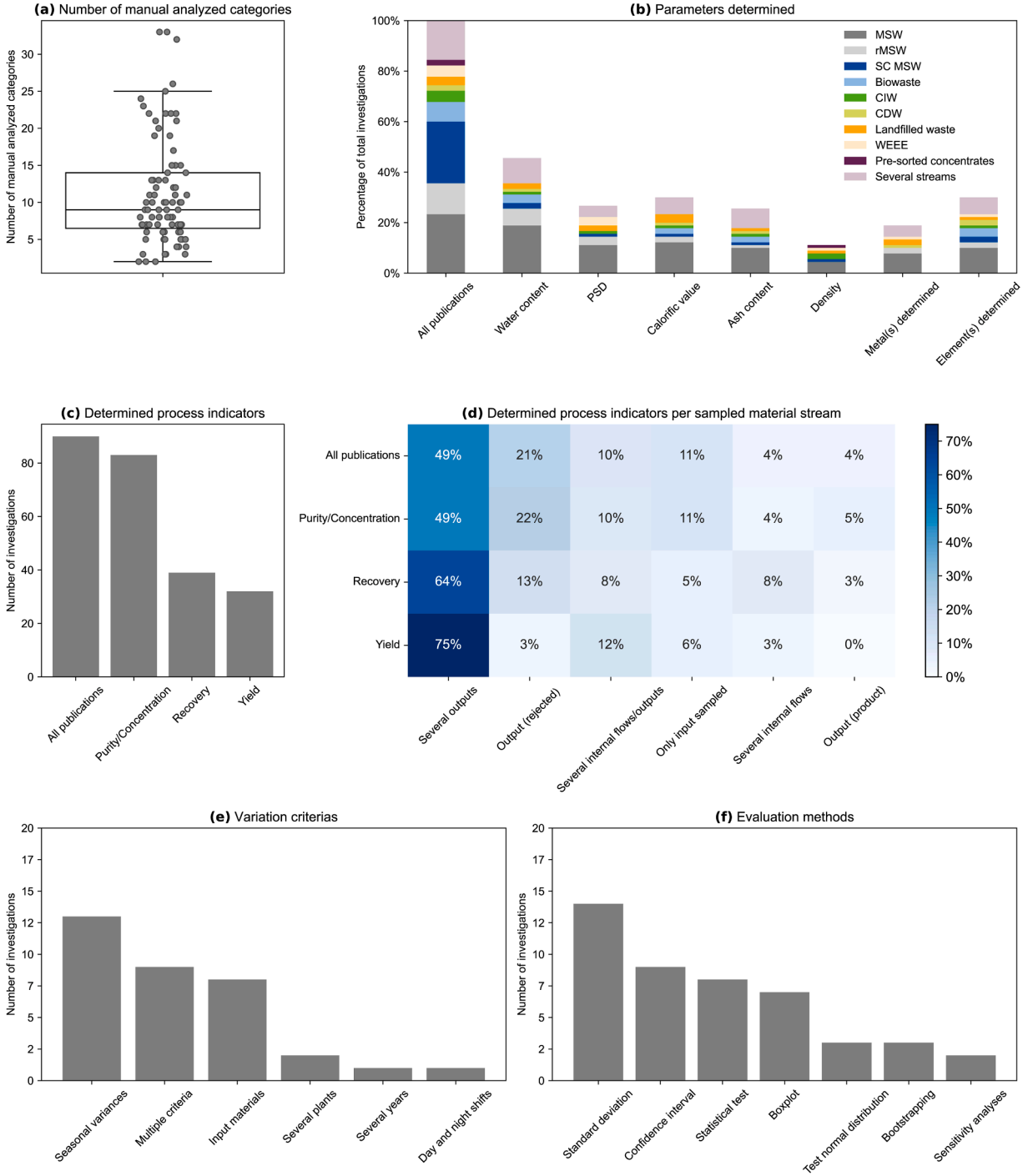


Fig. 6. Data extracted from investigations (case studies) addressing the practical application of sampling and manual analysis to assess MWP, identified through the database review, classified as Category 3 publications (cf. Fig. 2). This figure depicts examined parameters and evaluation criteria employed during the sampling of MWP, including (a) number of manually analyzed categories, (b) number of investigations that additionally determined parameters beside the manual analyses related to the investigated waste stream, (c) number of publications that assessed defined process indicators, (d) share of investigations reporting process indicators by type of sampled output or internal stream, (e) number of publications that determined additional variation criteria, and (f) number of investigations applying specific methods for evaluating manual sampling results (data included where available in the identfied investigations).

the Waste Framework Directive (The European Parliament and the Council of the European Union, 2025a). As a result, assessing single MWP operations or even entire plants is becoming increasingly relevant. This trend is also reflected in the identified DIN SPEC 91466-1, 2024-01-00, which may support quality assurance in sorting processes and thereby contribute to requirements such as those set out in Commission Regulation (EU) 2022/1616 for plastic pre-processing (The European Commission, 2022). However, translation into a full standard is still required.

Literature on further methodological concepts (Category 2, cf. Section 3.2) has been chiefly published before 2012 (cf. Fig. 7), with only three publications specifically addressing the sampling and manual analysis of MWP published after 2012 (cf. Section 3.2.5). In contrast, most investigations on the practical application of MWP assessment (Category 3, cf. Section 3.3) have been published after 2012 (cf. Fig. 7), suggesting a growing interest in this topic. The body of publications on the methodological development of MWP assessment by sampling and manual analyses remains limited, as evidenced by a closer examination of the identified literature on further methodological concepts (Category 2, cf. Section 3.2). Several publications addressed Gy's TOS, methods for determining sample size and sample numbers, and approaches to sample compressed waste such as bales, with some of these methods reflected in existing sampling standards. However, only a limited number of approaches are directly applicable to sample and manually analyze MSW to assess MWP, and no comprehensive methodological framework for assessing MWP could be identified. Regarding the determination of sample sizes and numbers, substantial methodological heterogeneity was also observed in case studies on the practical implementation of MWP assessments (Category 3, cf. Section 3.3, particularly Fig. 5(b) - (e)). Generally, the identified case studies employed different methodological approaches (cf. Section 3.3.2) and assessment techniques (cf. Section 3.3.3), often within small author networks focused on specific waste streams (cf. Fig. 3(b)). Moreover, evaluation procedures for manual analysis were applied only to a limited extent (cf. Fig. 6(f)). From the authors' perspective, although several concepts have been identified including the TOS, methods for defining sample numbers and sample sizes (cf. Sections 3.2.1 and 3.2.2), and evaluation techniques (cf. Sections 3.2.5 and 3.3.3), these approaches should be examined and validated further to determine whether, and in what form, they can be applied to different coarse household waste (particle size approximately $>$ 120 mm, often heterogeneous) sampled from continuous material streams for manual analysis in the context of MWP assessment. Ideally, any theoretically developed procedures should subsequently be validated using data from waste sampling campaigns. A method informed by these findings could support more comparable data across investigations assessing MWP through sampling and manual analysis.

3.4.2. *Implications for the development of methods to assess mechanical waste processing*

Although full sampling guidelines cannot be developed within the scope of this publication, the work offers initial methodological implications that may guide the design of future MSW sampling and manual analysis frameworks to assess MWP.

Regarding methods for defining categories for manual analyses, relevant publications were identified that developed methodological specifications for the analysis especially of unprocessed household waste (cf. Section 3.2.3); these approaches would, in principle, be transferable to the assessment of MWP. However, the evaluation of the number of manually analyzed fractions in the identified case studies reveals a high degree of variability (cf. Fig. 6(a)). One likely reason is that the specific sampling goal plays a predominant role in MWP sampling. For example, when assessing the effectiveness of a process, the purity of a product stream, or the suitability of a processed material for a recycling process, tailored categories for manual analyses are defined based on the specific research aim and, therefore, the sampling goal. The sampling goal also influences the selection of the streams being sampled. Evidence from investigations on the practical assessment of MWP (cf. Section 3.3) indicates that studies aiming to characterize overall plant performance or recovery potentials of specific materials typically sampled multiple streams, while studies with a more specific focus (assessing specific non-product fractions or the input) tended to focus relatively more often on an individual stream (cf. Supplementary material 5). Consequently, the sampling goals identified in Fig. 5(a) are a decisive factor in the methodological design of sampling procedures for MWP assessment. They can contribute to the development of methodological frameworks, with some sampling goals potentially consolidated where appropriate. In addition to sampling goals, the type of waste streams introduces distinct methodological requirements. For instance, depending on the waste stream, different additional parameters were determined alongside the manual analysis (cf. Fig. 6(b)). Accordingly, methodological specifications should be differentiated by waste stream and, where relevant, by plant type (cf. Fig. 4(c)). For example, sampling residual waste in MBTs poses methodological demands different from those in MRFs.

Additionally, various approaches were identified that more precisely define the practical sampling procedures, i.e., the act of taking samples relevant for assessing MWP. These approaches include both sampling compacted waste (primarily bale sampling by drilling, cf. Section 3.2.4) and sampling from continuous waste streams, e.g., from conveyor belts, at belt discharge points, or by using dedicated sampling devices. For sampling from continuous waste streams, specifications were identified both in standards (cf. Section 3.1) and in publications on further methodological concepts (cf. Section 3.2.5). These approaches may be applied directly depending on the waste stream. However, it is essential to ensure sufficiently high temporal resolution to reduce the likelihood of correlation between neighboring samples (cf. Section 3.2.5) and to capture time-dependent trends. Depending on the specific application, time-dependent (systematic) variations may be significant, and point-based cross-sectional evaluation would be insufficient. Appropriate analytical methods can help identify such effects (e.g., variograms used in the TOS, cf. Section 3.2).

Variation criteria with the potential to produce time-dependent trends in MWP assessments were derived from the case studies (Category 3, cf. Section 3.3) and are illustrated in Fig. 6(e). Seasonal variation was considered in 13 investigations. Input variation (including differences across settlement structures) was accounted for in 8 investigations, though in some, only the input was sampled and the effects on the output streams were not examined. This low number of investigations is noteworthy because stratification is frequently recommended when sampling unprocessed household waste (e.g., (Dahlén and Lagerkvist, 2008; European Commission, 2004)). Several reasons may explain this observation. First, depending on the sampling goal, stratification may not be necessary. For instance, if the aim is solely to evaluate a specific output stream and it can be assumed that performance remains stable despite certain fluctuations in the input, systematic stratification may not be required. Second, stratifying by settlement-structural factors is sometimes difficult or even impossible in practical plant settings. For example, if a plant uses a low-level bunker for the input material, keeping waste from different settlement structures separate may not be feasible. However, if standards are to be established, it should be carefully assessed whether, and to what extent, settlement-structural differences and other variation criteria need to be considered in MWP assessment. For residual waste, such differentiation may be necessary, e.g., due to seasonal compositional variability. In contrast, recent findings from LWP sampling campaigns (input to LWP sorting plants) from Austria suggest that the relative composition varies only modestly across settlement structures, seasons, and years (Gabriel et al., 2025; Kuhn et al., 2026), implying that the relative composition of output streams from LWP sorting plants may also be affected only to a limited extent. Consequently, the relevance of variation criteria that could introduce time-dependent trends in MWP assessments should be evaluated distinctly for each waste stream and sampling goal.

Another essential aspect in developing frameworks for sampling and

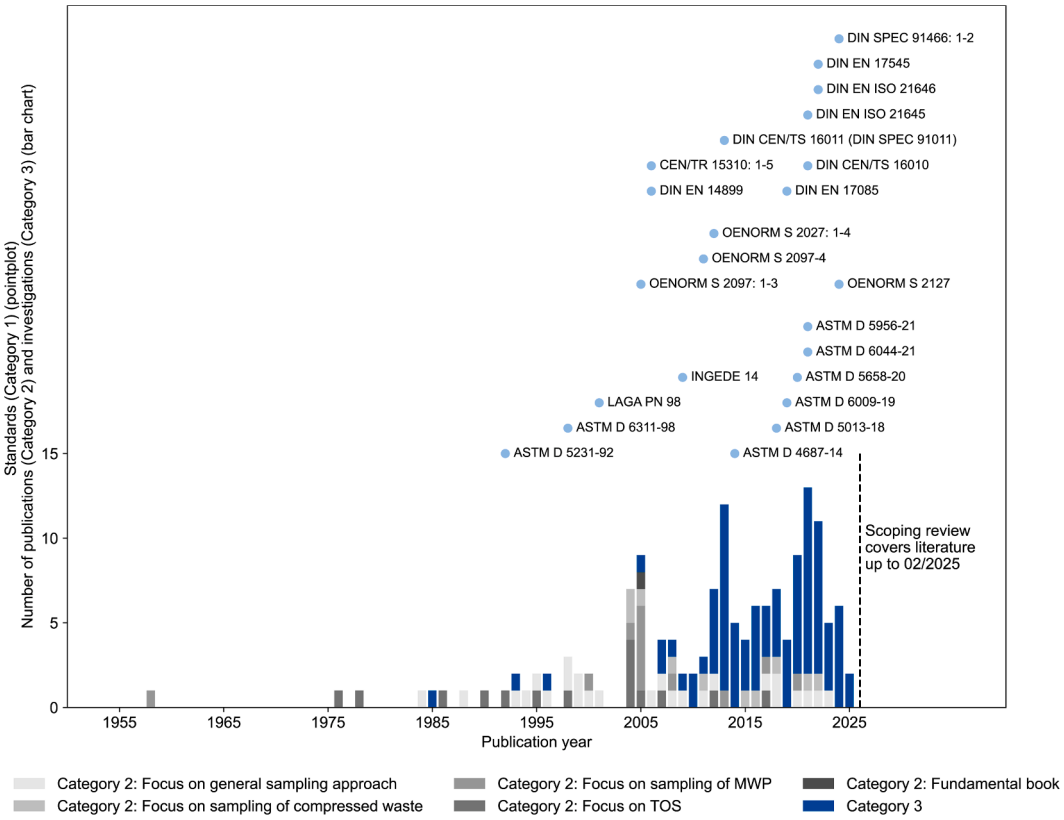


Fig. 7. Time evolution of all identified publications included in the scoping review. The identified standards (Category 1) are shown as point plots. The literature assigned to Category 2 (further methodological concepts) and Category 3 (case studies on assessing MWP) is displayed as bar charts, indicating the number of publications (Category 2) and investigations (Category 3) published per year.

manual analysis to assess MWP concerns the process indicators used. A proposal for a basic set of indicators was provided in Section 3.3.3, Eqs. (5) - (10), and includes purity/concentration, recovery, and yield. A major challenge in evaluating these process indicators within the identified case studies (Category 3, cf. Section 3.3.3) was the extremely heterogeneous terminology. For this reason, an overview of existing synonyms was compiled, and an initial approach to harmonizing the terminology, both for the process indicators and for several other relevant terms, is presented in Supplementary material 3. From the authors' perspective, such harmonization is urgently required to improve the comparability of MWP assessments.

Overall, the review provides a solid overview of existing evidence, and therefore a first foundation for deriving methods for MSW sampling and manual analysis to assess MWP. The authors propose examining and comparing existing identified methodological approaches and evaluation methods, and validating their applicability with data obtained from sampling campaigns. A distinction should be made according to waste stream and, where relevant, plant type. In addition, the sampling goals should be considered as a key criterion, as they determine both the material categories for manual analysis and the material streams that need to be sampled. Relevant variation criteria should be evaluated with respect to their impact, their practical feasibility in plant-scale sampling, and their potential to introduce time-dependent trends. As part of such standardization efforts, the harmonization of defined process indicators and the terminology used should also be pursued. Building on these considerations, the following questions for future research emerge:

- How well can existing methodological approaches, particularly with regard to sample size, sample number, and (statistical) evaluation methods, be transferred to the sampling of different coarse, heterogeneous wastes (particle size approximately > 120 mm) from continuous material streams to conduct manual analyses for the assessment of MWP?
- How can the sampling of MWP be standardized based on waste stream, plant type, and sampling goal, and what level of detail is required for such standardization?
- Is a differentiation according to additional variation criteria, such as settlement structure and season, practically feasible, and what impact might it introduce?
- Which terms and assessment indicators are relevant for the sampling and manual analyses of MWP, which of these should be harmonized, and how can such harmonization be comprehensively implemented?

4. Conclusion

The assessment of mechanical waste processing operations (MWP) serves an increasingly broad range of purposes, including providing data for environmental assessments, optimizing processes, validating modeling approaches, and determining material recovery potentials. To assess MWP, sampling and manual analysis are frequently applied. To examine the current state of the art on the sampling and manual analysis of non-hazardous municipal solid waste (MSW), with a specific focus on the assessment of MWP, a scoping review was conducted. Based on systematic search criteria, $n = 12{,}603$ publications were identified and screened. Ultimately, $n = 33$ standards, $n = 63$ publications on further methodological concepts, and $n = 80$ publications (90 investigations) related to MWP sampling were extracted and evaluated.

Several identified standards focus on the sampling of trucks, static bulk materials, and specific MSW types. In addition, two standards were identified that address the sampling of MWP, namely, MBT plants with a focus on determining stability parameters and a preliminary standard concerning the sampling of LWP sorting plants for certification. Furthermore, several standards at least partially address sampling from

continuous material streams. Among publications discussing further methodological concepts for sampling and manual analysis, several focused on Gy's Theory of Sampling. Other studies described methods for determining sample size and the required number of samples. Additionally, several publications investigated the sampling of compressed waste (e.g., bales). Some of the methods proposed in these publications are also reflected in existing sampling standards. Different publications addressing methodological approaches to MWP assessment were identified. However, no comprehensive methodological framework for sampling and manual analysis to assess MWP was found. [RQ1] The evaluation of publications dealing with the sampling of MWP revealed that research is often conducted within relatively small author networks focused on specific waste streams. Moreover, there is substantial heterogeneity in methodology, particularly in the selection and documentation of sampling procedures. A considerable variation in terminology was also observed, leading to uncertainty in the interpretation of results (e.g., regarding evaluated process indicators). [RQ2] Subsequently, the identified evidence was contextualized, and initial methodological implications were derived that may guide the design of future MSW sampling and manual analysis frameworks to assess MWP. The authors propose distinguishing sampling methodologies by waste stream, plant type, and sampling goals. Relevant variation criteria should be evaluated with respect to their impact, practical feasibility at plant scale, and potential to introduce time-dependent trends. Standardization efforts should also include harmonizing process indicators and terminology. Building on these considerations, future research areas were defined. [RQ3]

In summary, a wide range of different literature and approaches for the sampling and manual analysis of non-hazardous MSW to assess MWP was identified. In the waste management sector, however, the application of specifications often requires balancing the theoretically optimal procedure against practical and economic feasibility, which may ultimately come at the expense of data accuracy. Nevertheless, from the authors' perspective, unified methods specifically tailored to the assessment of MWP through sampling and manual analysis could improve data quality and enhance comparability across investigations. This scoping review provides structured evidence of the literature on sampling and manual analysis of non-hazardous MSW, with a particular focus on assessing MWP, thereby offering a first basis for developing harmonized methodological frameworks. It is intended to support the improved planning and execution of sampling campaigns, especially for young researchers, ultimately enhancing data quality and the application of assessing MWP.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used DeepL SE, Grammarly Inc. and ChatGPT in order to improve readability and language and ChatGPT to improve Python code. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Alena Maria Spies: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steffen Herbert Schmädecker:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Nikolai Kuhn:** Writing – review & editing, Validation, Methodology, Conceptualization. **Karoline Raulf:** Writing – review & editing, Validation, Conceptualization. **Gerald Koinig:** Writing – review & editing. **Kathrin Greiff:** Writing – review & editing, Supervision, Funding acquisition. **Roland Pomberger:** Writing – review & editing, Supervision, Funding acquisition.

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.

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Supplementary materials

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Data availability

No data was used for the research described in the article.

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