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ORIGINAL ARTICLE

Scenario analysis tool for estimating future waste composition and amounts toward a circular economy

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Abstract

Municipal solid waste management has a potential to increase circularity by reduction of virgin material extraction and use of secondary materials. A scenario analysis tool was developed to assess whether circular economy goals are attainable with the existing infrastructure and technologies by calculating sorting and recycling rates using waste amount and composition estimations. Three scenarios, Current Road (business as usual), Circular Road (improved sorting) and Frugal Road (waste reduction), were developed and implemented. Sorting rates targets for food waste are achieved in all scenarios. For plastic, sorting rate targets are achieved only for Circular and Frugal, while European Union recycling targets are not reached in any, showing the important role of recycling efficiency. Policy makers can use the scenario development approach of this study to evaluate if circular economy goals are attainable with the current system and assess the impact of key factors such as waste generation and sorting behavior. The scenario analysis tool can be utilized to simulate the effects of different measures in the waste amounts and composition, which is crucial for the planning of the future management system. Further, sorting and recycling rates provide quantitative information about the circularity gap and qualitative information on bottlenecks and opportunities.

Keywords Municipal solid waste · Waste management · Tool · Circular economy · Scenario analysis

Introduction

Background

Municipal solid waste (MSW) management has an important role in improving circularity through the implementation of circular economy principles such as reduction of virgin material extraction and use of secondary materials, as stated in the latest Circularity Gap Report (2023) [1]. Large quantities of diverse materials are handled in the MSW system with a high potential for reuse and recycling. Circularity of MSW management depends on various factors, such as source sorting of waste which is affected by social factors [2], recyclability of materials, and recycling efficiency of the recycling process [3]. All these factors must be considered for a circular MSW system.

Sorting and recycling targets constitute the key circular economy goals for MSW fractions. Targets for Norway are given in Table 1 [4, 5]. It is important to estimate sorting and recycling rates with a possibility of investigating whether the targets are attainable given certain boundaries.

Table 1 shows that 14.6% of Norwegians did not have separate food waste collection in 2017, indicating a large potential for improved sorting. There is also a specific target only for food: to halve waste in the entire production and supply chain, and the post-harvest losses including MSW [6]. Food waste is the largest fraction in household residual waste, showing a great unexploited potential as the share can be as high as 50 wt.% [7]. Correct food waste sorting will influence both the residual and food waste management systems, such as the required installed capacity for MSW incineration and biogas plants (the main treatment method for food waste in Norway) [4]. The circularity potential in food waste goes beyond the biogas, as digestate, a co-product of biogas production, can be used for soil enhancement due to its organics and minerals content.

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Table 1 Targets and current situation (2017) for MSW fractions in Norway [12, 13]

MSW fraction	Current situation (percentage of population with collection)	Current situation (sorting rate)	Target for the municipalities
Paper	99.8% doorstep collection, 0.2% drop-off collection	76%	80% and 85% source-sorting by 2028 and 2035. 75% and 85% recycling by 2025 and 2030 (packaging).
Glass	55.1% doorstep collection, 44.4% drop-off collection, 6.5% central sorting, 0.5% no sorting	78%	85% and 90% source-sorting by 2028 and 2035 (packaging). 70% and 75% recycling by 2025 and 2030 (packaging).
Metal	55.1% doorstep collection, 44.4% drop-off collection, 6.5% central sorting, 0.5% no sorting	39%	85% and 90% source-sorting by 2028 and 2035 (packaging). 70% and 80% recycling by 2025 and 2030 (iron packaging). 50% and 60% recycling by 2025 and 2030 (aluminum packaging).
Plastic	87.3% doorstep collection, 0.2% drop-off collection, 12.5% central sorting	28%	50%, 60%, and 70% source-sorting by 2028, 2030, and 2035. 50% and 55% recycling by 2025 and 2030 (packaging).
Textiles	9% doorstep collection, 89.9% drop-off collection, 1.2% no sorting	0.3% (estimation)	Separate collection from 1. January 2025.
Food waste	85.4% doorstep collection, 14.6% no sorting	44%	Separate collection or home composting from 31. December 2023. 55%, 60% and 70% source-sorting by 2025, 2030 and 2035.
Garden	26.1% doorstep collection, 72.8% drop-off collection, 1.1% no sorting	74%	Separate collection with no specific target.

Table 1 also shows that 12.5% of Norway did not have separate plastic waste (which is up to 95% packaging [3]) collection in 2017, but plastic waste was collected together with residual waste and sorted at a central sorting facility. The gap between the current recycling rate and the target is largest for plastic, indicating the need for improvement, as also shown in our earlier study [8].

In accordance with the waste reduction ambition, the residual waste fraction has an important role in achieving circularity. Residual waste contains both correctly sorted residual waste, namely unrecyclable fractions, but also incorrectly sorted recyclable fractions. Therefore, it is crucial to connect the amount to information about its composition to estimate the recycling potential correctly. The main residual waste treatment in Norway is incineration with energy recovery (WtE, Waste-to-Energy). Incineration of certain fractions might impose health and safety risks, cause environmental challenges, and create operational issues in the plant. In this article, the focus will be on the residual, food, and plastic waste fractions.

Aim and novelty

The construction and implementation of waste management scenarios, using models and software tools, aims to support decision-making and the selection of best practices. Existing scenario analysis studies mainly focus on the evaluation of different managements strategies to maximize environmental performance, for a limited number of MSW fractions (mostly residual waste) from a single source (doorstep collection from household) without considering impurities in the source-sorted waste fractions such as plastic in food waste. Wang and Becidan (2021) developed scenarios including population change, waste generation per inhabitant, and recycling targets as stated in the EU's Circular Economy Action Plan and suggested that it would be beneficial to consider consumer behavior in future scenario work [9]. Engelmann et al. (2022) developed scenarios with different MSW compositions and treatment methods using GHG emissions, energy savings, and economic impacts as the evaluation criteria without using historical data nor considering sorting and recycling rates [10]. Zibouche et. al (2023) performed life-cycle assessment for different solid waste management options, treating MSW as a single stream with a constant composition [11]. In the work by Gombojav and Matsumoto (2023), plastics contaminated with other waste were evaluated as part of MSW fractions. Two composition values for summer and winter seasons were used as constant and only the change in amount was considered in alternative treatment scenarios with no regard of source of generation [12]. Yamada et al. (2023) took the generation sources into account when assessing the management scenarios to achieve zero greenhouse gas (GHG) emissions by 2050 both for municipal and industrial waste [13].

The background statistical data used for scenario analysis need to be sound and accurate. The composition of each waste container or the impurity of the sorted waste fraction is necessary to obtain a realistic overview of the total situation, considering all fractions in the MSW system. Source of waste generation should extend only from households (doorstep collection) to include waste from collection points (drop-off collection) and Commercial and Industrial (C&I)

waste (with varying proportions depending on the area) also being part of the MSW. Thus, it is crucial to collect and link these different data sources to describe the system precisely, despite data uncertainty challenges [14]. Furthermore, it is important to perform the scenario analysis at the right geographical resolution so that results are detailed and accurate enough to support decision-making not only at an international (EU) or national level, but also at the city/regional level [9]. In this study, we chose a typical Norwegian town as the analysis area.

The aim of this study is twofold: (i) To precisely describe the MSW system of a Norwegian town by analyzing and linking different data sources, and (ii) to develop a scenario analysis tool for assessing whether the circular economy goals are attainable with the existing infrastructure and technologies, by estimating future sorting and recycling rates based on MSW compositions and amounts for scenarios with different principles.

The originality of this work is due to these aspects; (1) a detailed description of a MSW management system from generation to end treatment by linking different types of data to define the composition and amounts at the subfraction level generated by various sources; (2) the contamination of sorted waste fractions by "other waste" is considered using waste composition analysis of not only residual waste but also recyclable fractions; (3) sorting and recycling rates are calculated for all MSW subfractions using specific recycling efficiencies that accounts for material impurities, nonrecyclable parts and recycling technology; (4) the development of a scenario analysis tool and application for a representative Norwegian city using information that is mainly available in Norwegian, thus contributing to scientific literature with local data; (5) the in-depth analysis of historical data to develop "what-if" scenarios based on the accurate description of the MSW system; and (6) development and implementation of a business-as-usual scenario using historical trends as well as ambitious scenarios with major changes to assess whether circular economy targets are attainable.

Methodology

The scope of this article is the MSW generated in a town in central Norway. The reference year 2019 was chosen to avoid any covid effect. However, covid does not seem to have a significant effect according to a recent study [14]. The town had a population of approximately 15500 and was chosen to be representative for the country, i.e., it had a population density of 1455 people/km^2 in 2019, while the average for 359 settlements in Norway was 1244 people/km^2 [15].

Terminology

Terms used in this article are listed below [16].

MSW (municipal solid waste) is the mixture of household and household-like C&I waste that is collected by municipalities.

Household waste is waste from private households.

Household-like Commercial and Industrial (C&I) waste is waste from both private and public businesses, that has similar properties to that of household waste.

Waste fractions refers to the main waste fractions (see Fig. 1). Descriptions of main fractions can be found in statistics Norway [16].

Subfraction is a subcategory of a waste fraction. Subfractions of paper, plastic, food, metal, and glass are considered in this study.

Waste composition refers to the weight-percent distribution of waste.

Doorstep collection refers to waste bins and containers placed near the waste source.

Drop-off collection consists of recycling points and civic amenity sites to which the consumers bring their waste.

Waste sorting means sorting of a waste fraction that has a recovery potential, which can be done where waste is generated (source-sorting) or in dedicated plants after collection (central sorting).

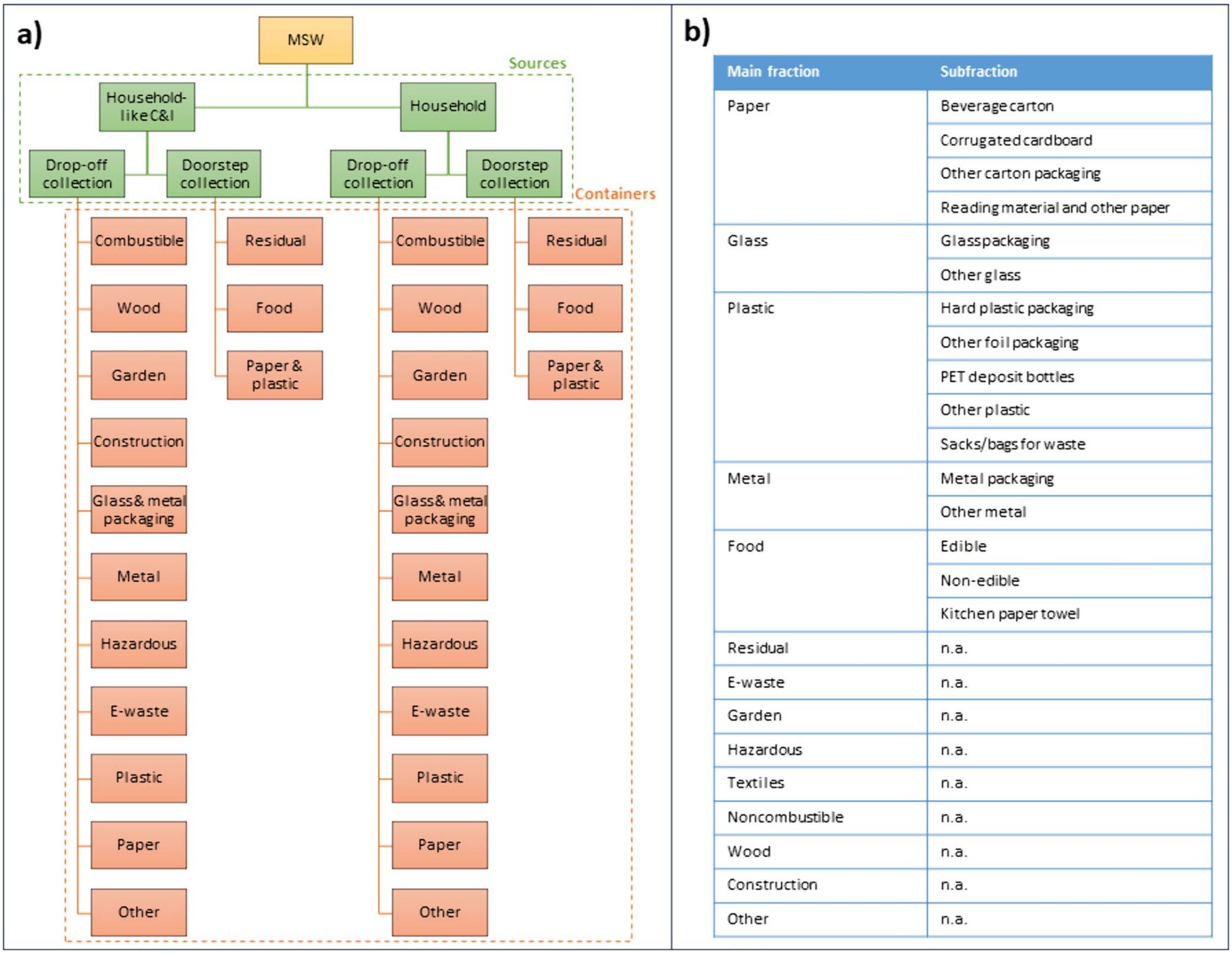
Waste recycling refers to material recovery of recyclable waste fractions.

Recycling efficiency is a measure (in %) of what is recycled after cleaning and pre-processing.

Waste collection system and background data

The studied town's 2019 waste system consisted of a doorstep collection system for four fractions, with the remaining fractions collected via drop-off. The doorstep collected fractions were residual, food and paper waste, collected in separate containers, and plastic waste, collected in a separate plastic bag that is collected with the paper container [17]. Some apartment buildings had large common containers, where the plastic was discarded in the same container as the paper, with the plastic in tied-up plastic bags and the paper left loose [18]. This latter solution was found to give poorer outcomes both in terms of collection rate of plastic (kg/inhabitant) and correct sorting [19]. Glass and metal packaging waste was delivered to central recycling points, and all other fractions to civic amenity sites by the inhabitants.

The amounts of different waste fractions were obtained from Statistics Norway [20, 21] for 2019, and the split between the different collection systems is based on data for 2020 and 2021. This was done due to a change in the data collection system in 2019. Waste composition analyses were gathered for the following fractions: Residual



Main fraction	Subfraction
Paper	Beverage carton
	Corrugated cardboard
	Other carton packaging
	Reading material and other paper
Glass	Glass packaging
	Other glass
Plastic	Hard plastic packaging
	Other foil packaging
	PET deposit bottles
	Other plastic
	Sacks/bags for waste
Metal	Metal packaging
	Other metal
Food	Edible
	Non-edible
	Kitchen paper towel
Residual	n.a.
E-waste	n.a.
Garden	n.a.
Hazardous	n.a.
Textiles	n.a.
Noncombustible	n.a.
Wood	n.a.
Construction	n.a.
Other	n.a.

Fig. 1 Organization of the waste collection system with sources and containers (**a**) and main waste fractions and subfractions (**b**)

[22], food [23], paper and plastic from doorstep collection [22, 24, 25]; glass and metal packaging from central collection point [26]; combustible waste and plastic from civic amenity site [27]; and C&I waste fractions residual waste [22], plastic and paper [22].

The background data consisted of the amounts and composition from 28 different waste containers containing 14 distinct waste fractions, for both household and household-like C&I waste, as well as more detailed data on 16 subfractions originating from 5 waste fractions (paper, glass, plastic, metal, and food). The data structure is illustrated in Fig. 1.

The composition of each waste container (Fig. 1a) covers the *actual* amount of each waste fraction and subfraction listed in Fig. 1b.

Scenario descriptions

Current road

This scenario can be considered as "business as usual", as it is based on historical changes in waste subfractions for each waste container. Annual changes were calculated from 2015 to 2019 and their average was used as the input to the tool. Municipality borders changed throughout years; therefore, changes in waste fraction and subfraction amounts were calculated on a per person basis. Population change (+ 0.2% per year) was kept constant in all three scenarios. Annual changes in *sorted* waste fractions per person is given in Table 2.

Similar annual changes were applied to each subfraction, except 'reading material and other paper' (a paper waste

Table 2 Annual changes in container weights by waste fraction per person used in Current Road and Circular Road scenarios

Container by waste fraction	Annual weight change
Residual	– 2%
Food	+ 4%
Plastic	+ 5%
Paper	– 4%
Glass	+ 2%
Metal	+ 4%
E-waste	– 3%
Garden	– 4%
Hazardous	+ 1%
Wood	– 1%
Construction	0%
Other	0%

subfraction) set to − 7% and 'metal packaging' (a metal waste subfraction) to 2% based on historical trends.

Circular Road

Circular Road assumes a drastic improvement in consumers' sorting behavior due to an increased awareness of the importance of correct sorting. The focus is quantification of the effects of improved source sorting. The changes in total amounts of subfractions were kept the same as in Current Road; however, they were "moved" to the correct containers to reflect better sorting by households. The improvement in sorting behavior was set to 10% for all recyclable fractions. For example, every year from 2020, 10% of the plastic discarded in the wrong container (residual waste container) is diverted to the right container (plastic waste container). The sorting system in place is assumed to be unchanged, i.e., no new containers or sorting of new fractions.

Frugal Road

Frugal Road assumes a drastic change in consumer behavior and lifestyle, with increased awareness of consumption and waste, resulting in reduced household consumption. Increased consumer awareness also improves waste sorting, as the more aware consumers are assumed to be, the more aware they will be regarding what the recyclable and reusable/edible waste fractions are. The focus is on quantification of the effects of waste generation reduction combined with increased sorting awareness. The assumptions below were implemented in the scenario analysis tool to reflect this evolution:

- All incorrectly sorted waste fractions, except plastic waste bags, are eliminated from all containers;
- Edible food waste and reading material subfractions are eliminated from their respective containers, due to increased awareness about food waste and a shift from printed to digital reading material;
- Annual changes in waste fractions are kept as in Current Road and Circular Road except when the rate of change was positive. In that case, the rate was set to 0% to reflect the changing, more frugal behavior.

Above-mentioned fractions were assumed to disappear almost entirely from the above-mentioned containers by 2035. There will be small amounts remaining in the containers due to human error. The rate of decrease was specified individually for each and applied relative to the previous year for each year from 2020 to 2035.

Scenario analysis tool

An Excel-based scenario analysis tool was developed using the background data described in section "Waste collection system and background data" as the basis for implementation of the scenarios explained in section "Scenario descriptions". In the first step of the calculations (Figure in appendices), the amounts of each subfraction in every container was calculated for each year from the reference year (2019) until the chosen time horizon (2035), using the annual changes given in Table 1 and/or scenario descriptions for waste fractions and population. The calculation of subfraction amounts is done using Eqs. 1 and 2.

$$change_{i,j,net} = \left(\left(100\% + change_{pop}\right) * \left(100\% + change_{i,j}\right)\right) - 100\%, \quad (1)$$

where $change_{i,j,net}$ is the annual net change per person in the amount of subfraction i in container j; $change_{pop}$ is the annual population change; and $change_{i,j}$ is the annual change per person in the amount of subfraction i in container j, which was assumed to be constant for each year. The subscript i denotes the recyclable subfraction that is $i = 1, .., 18$ that are given in Table 3. The subscript j denotes container that is $j = 1, .., 28$ for containers shown in Fig. 1.

$$amount_{i,j,k+1} = amount_{i,j,k} * \left(1 + change_{i,j,net}\right), \quad (2)$$

where $amount_{i,j,k}$ and $amount_{i,j,k+1}$ is the amount of subfraction i in container j at year k and $k + 1$, respectively. The subscript k denotes the year that is $k = 2019, .., 2035$.

In the second step of the calculations (Figure in appendices), sorting rate (%) and recycling rate (%) are calculated using Eqs. 3 and 4, respectively. The sorting rate of a recyclable waste fraction is defined as the ratio between the amount of correctly sorted waste and the total amount of generated waste of the respective fraction. The recycling rate is the multiplication of the sorting rate and recycling

Table 3 Recycling efficiency of recyclable subfractions

Main fraction	Subfraction	Recycling efficiency (%)	Source
Paper	Beverage carton	93	[29]
	Corrugated cardboard	98	
	Other cardboard packaging	97	
	Reading material and other paper	81	[30]
Plastic	Hard plastic packaging	66	[31]
	Other foil packaging	55	
	PET deposit bottles	44	
	Other plastic	16	
	Sacks/bags for waste	64	
Food	Edible	100	Assumption
	Non-edible	100	
	Kitchen paper towel	100	
Glass	Glass packaging	99	[29]
	Other glass	99	
Metal	Metal packaging	81	[29]
	Other metal	81	
Garden	Garden	100	Assumption
E-waste	E-waste	40	Assumption

efficiency, since it should be calculated as the ratio between the amount of waste actually recycled and total amount of generated waste, according to the most recent EU Directive [28].

$$SR_{i,k} = \frac{\sum_{j=1}^{Jright} amount_{i,j,k}}{\sum_{j=1}^{Jtotal} amount_{i,j,k}} * 100\%, \tag{3}$$

where $SR_{i,k}$ is the sorting rate of subfraction i in year k. $Jright$ is the correct container for subfraction i, and $Jtotal$ is all containers containing subfraction i.

$$RR_{i,k} = SR_{i,k} * Reff_i, \tag{4}$$

where $RR_{i,k}$ is the recycling rate of subfraction i at year k. $Reff_i$ is the recycling efficiency of subfraction i, given in Table 3. Recycling efficiency is a measure of what is recycled after cleaning and pre-processing, as there are impurities and non-recyclable materials (such as composite materials) in the sorted waste [3].

It is important to note that food waste and garden waste recycling rates are assumed to be 100% due to generation and utilization of digestate in the former and compost in the latter. Both are assumed to contain nutrients of these waste fractions that are used up by the microorganisms in soil over time even though they are heterogenous mixtures of materials with different degradation times, for example, shell and core of fruits and fruits in food waste; leaves and branches in garden waste.

Results and discussion

Waste amounts, compositions, sorting, and recycling rates are calculated for all fractions and subfractions. The results presented here focus on residual, food and plastic waste.

Waste amounts

The scenario analysis tool implements the scenarios and estimates the resulting waste amounts. Annual subfraction amounts by container are calculated for 2019–2035, using equations 1 and 2 and the annual changes given in Table 2. Figure 2a shows the total amount of waste in all 28 containers (Fig. 1) in the scenario Current Road, that is 3% more than in the reference year, meaning that historical changes indicate the MSW will continue to increase if existing trends are to remain.

The household residual waste container has the most diverse waste content, with 21 waste subfractions (see Fig. 1) due to incorrect sorting. There are four different residual waste containers in the waste system, namely residual and combustible waste for household and C&I waste (Fig. 1). Figure 2b shows the sum of these four containers for the Current Road scenario. As can be seen in Fig. 2b, estimations (in dark blue) are in line with historical data (in light blue). The total amount of waste in residual waste containers in 2035 is estimated to be 1613 tons, which is 25% lower than the 2158 tons of the reference year. The collection fee is set based only on the size of the residual waste container [32], which may curtail the residual waste amount.

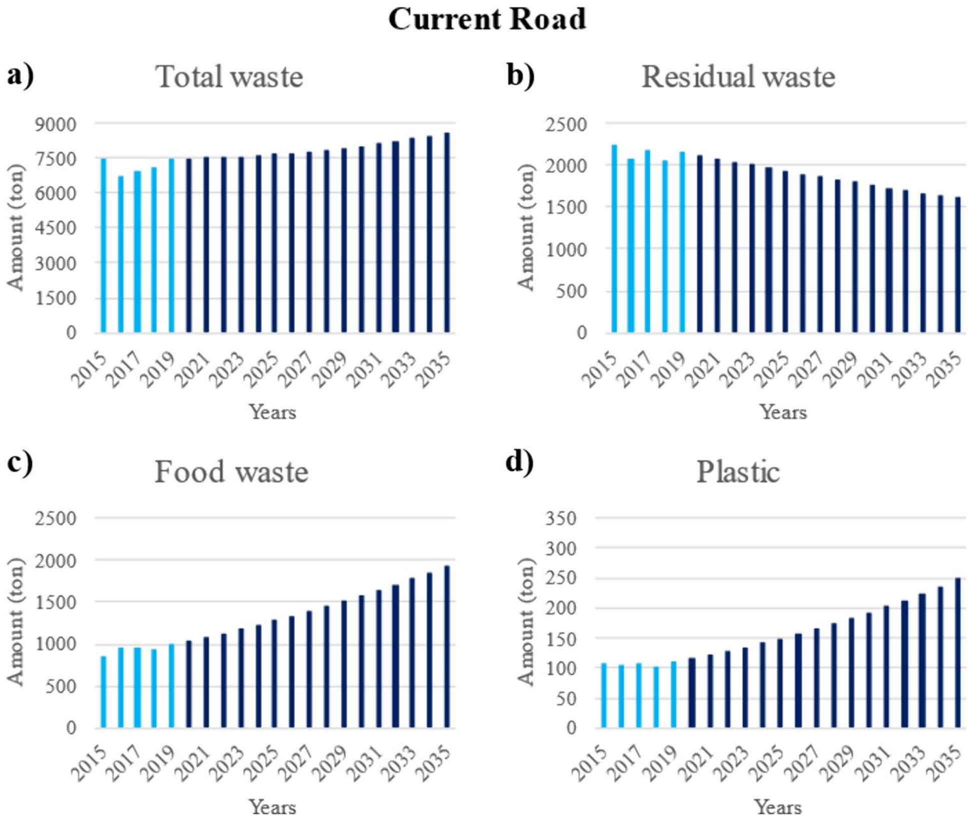


Fig. 2 Amounts of total waste (**a**), residual waste (**b**), food waste (**c**) and plastic (**d**) for Current Road scenario (in dark blue) together with historical data (in light blue)

Another factor can be that the MSW companies were rolling out doorstep collection of glass and metal, which was reported to reduce the amount of glass and metal found in the residual waste container [33]. Targeted communication, involvement, and guidance to citizens over time are also considered important.

There are two food waste containers (doorstep collection for households and C&I waste), and they contain six waste subfractions, namely residual waste, sacks/bags for waste (plastic), garden waste, edible food waste, non-edible food waste, and kitchen paper towel. The latter three subfractions are correctly discarded in the food waste containers, while the former three are a result of incorrect sorting. Figure 2c shows the sum of the two food waste containers for the Current Road scenario. The total amount of waste in the food waste containers in 2035 is estimated to 93% more than in 2019. This increase impacts both the waste collection and the treatment system. The installed capacity of biogas plants must be sufficient to treat this amount of food waste, including the incorrectly sorted subfractions which can be separated in a pre-treatment step at the expense of increased costs.

There are four containers for collection of plastic waste in the waste system: Plastic containers at drop-off collection, and paper and plastic containers as part of the doorstep collection system, for both household and C&I waste. Figure 2d shows the sum of these four containers for the Current Road scenario. The plastic waste containers also contain incorrectly sorted waste. The total amount of waste in the plastic waste containers in 2035 is estimated to be 249 tons, which is 124% more than the 111 tons in 2019. This significant increase will require higher capacity for the waste collection, sorting and treatment for plastic. Today, most of the plastic waste is sent abroad for recycling, either directly after collection, or via a central sorting facility. Incorrectly sorted waste in the plastic containers, thus, increases the environmental and economic costs substantially, considering the whole value chain. Incorrectly sorted fractions must be considered when planning for and operating central sorting facilities, as well as plastic recycling plants that can easily be overlooked or go uninvestigated in waste management phase.

Figure 3b shows that the total amount of waste in the residual waste containers for Circular Road is 44% lower than in 2019. The decrease is larger than in Current Road, as improved sorting behavior in the Circular Road scenario means that recyclable waste fractions are increasingly discarded in their correct containers (a 10% annual increase between 2019 and 2035). The total amount of waste in the food waste containers and plastic in plastic containers are estimated to be 111% and 202% more than in the reference year, shown in Fig. 3c–d.

For the Frugal Road scenario, Fig. 4a shows that the total waste amount is 38% lower in 2035 compared to the reference year 2019 after removing all subfractions (see section

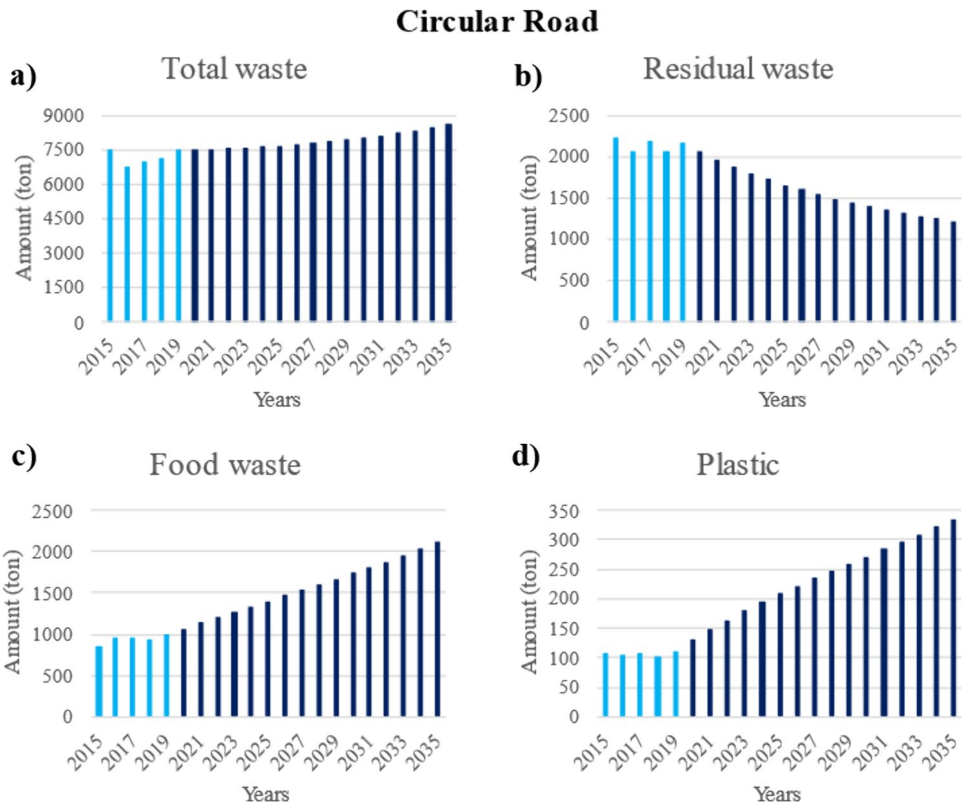


Fig. 3 Amounts of total waste (**a**), residual waste (**b**), food waste (**c**) and plastic (**d**) for Circular Road scenario (in dark blue) together with historical data (in light blue)

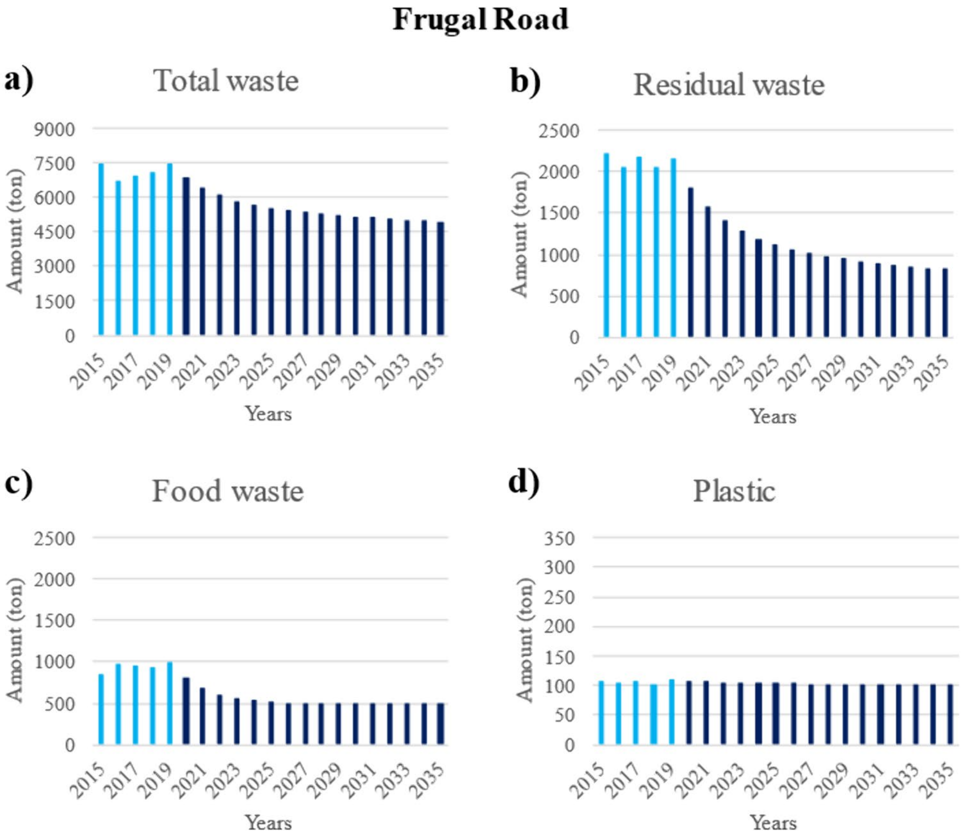


Fig. 4 Amounts of total waste (**a**), residual waste (**b**), food waste (**c**) and plastic (**d**) for Frugal Road scenario (in dark blue) together with historical data (in light blue)

“Scenario descriptions”) that can be reasonably eliminated from the waste system. The waste amounts found in the residual, food and plastic waste containers are estimated to be 62, 51 and 7% lower, respectively, in 2035 compared to 2019. Food waste reduction reaches the goal of 50% (which is set for the entire production and supply chain [6]) when edible food waste is eliminated in disposal part of household and C&I waste by 2030 as specified in Frugal Road.

To summarize, by 2035, the total waste amount is 38% lower in the Frugal Road scenario while it is 3% higher in Current and Circular Road. Residual waste is estimated to decrease in all three scenarios with Frugal Road having the largest decrease. The food waste amount is higher in both Current and Circular Road, while lower in Frugal Road compared to 2019. Finally, plastic is higher in all three.

Waste composition

The composition of each waste container, i.e., how much of each subfraction is found in a particular container, is estimated in the scenario analysis tool for each year from 2020 to 2035. The composition provides information about incorrectly sorted waste. This is crucial information to improve recycling: for planning and operating measures such as a central sorting plant. The contents of the residual waste container are incinerated in waste incineration plants. Thus, its composition gives information necessary for the estimation of the fossil vs biogenic carbon percentage [3], gas and particulate matter emissions. It may also impact bottom and fly ash formation in the plant [34], thus the potential for mineral and metal recovery from the ashes after incineration, which contributes to the circularity of the MSW system. It is important to note that recovery of materials directly from the raw waste stream is favorable rather than the recovery from the ashes after they are incinerated since recovery rates are lower due to quality degradation. For example, recycling efficiency of metal waste fractions is 81% (Table 3) while given as 41% (maximum) for metals recovery from bottom ash [35]. These aspects are directly related to costs (fees, consumables, etc.), environmental impacts, and health and safety (risk of explosion due to batteries, air quality, etc.). Incineration plant operation is highly influenced by the waste composition due to its effect on the heating value that is one of the main factors affecting output and profitability of a WtE plant. Its estimation improves plant operation, resulting in increased plant efficiency, and lower emissions and maintenance costs [36]. For the same reasons, during planning, scaling, and design of new incineration plants, residual waste composition needs to be considered carefully. Therefore, we focus on the composition of the residual waste container in this study, given in Fig. 5.

Figure 5a shows the composition of the residual household waste container for the reference year 2019. The residual waste content (the correct fraction for this container) is 36%. The second largest waste fraction is food waste (22%), showing a large recycling potential. The third largest fraction

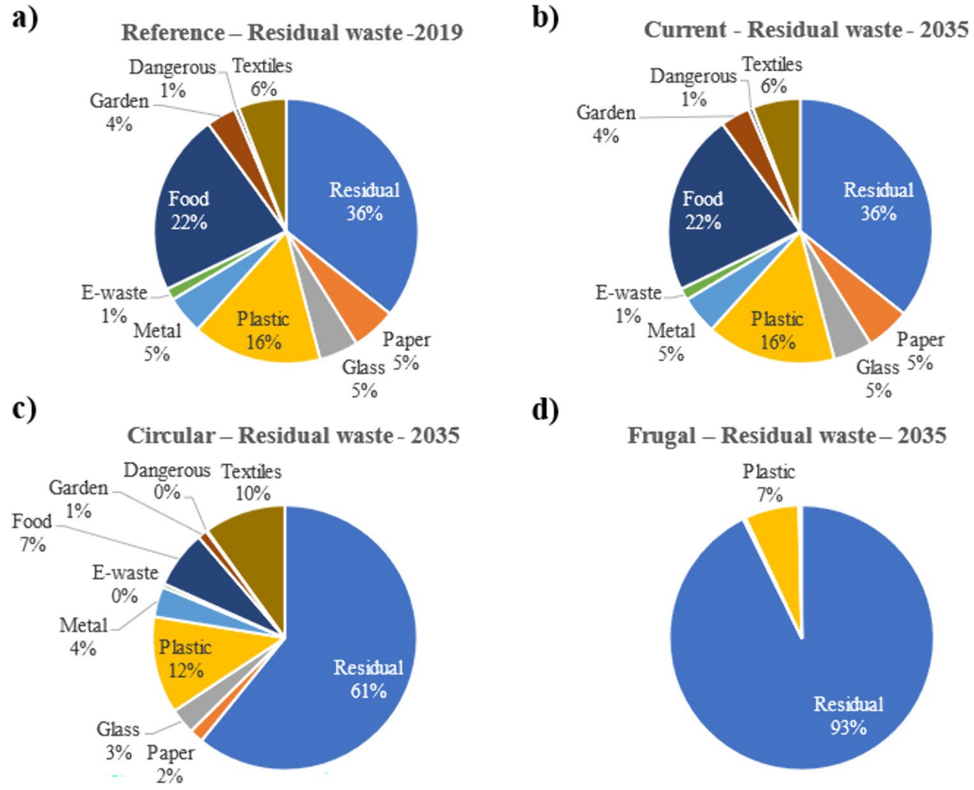


Fig. 5 Composition of residual waste in all years for reference year 2019 (**a**), Current Road (**b**), Circular Road (**c**) and for Frugal Road in 2035 (**d**)

is plastic (16%), which contributes to fossil carbon emissions together with textiles (6%).

Textiles require special attention since their amount in residual waste has been increasing steadily, and they must be collected and treated separately from 2025 [4]. In this study, only textiles found in the residual waste container are considered, as source-sorting done by consumers via drop-off collection points is currently handled by charitable organizations in the study area of this article, thus out of scope for MSW. However, it has been reported that 50% of textiles found in residual waste are reusable [4], showing a significant potential for circularity.

Garden waste (4%) can be valorized via biogas production or composting. Metal, glass and paper are recyclable waste fractions, each with a 5% share in the residual waste composition, showing an important recycling potential as well as a potential for metal recovery from the ashes after incineration even through lower recovery rate compared to recycling of raw waste streams. Both e-waste and hazardous waste have a 1% share. Even though their share is minor, the risk imposed by their presence in the residual waste is quite high. For example, batteries (e-waste) can cause explosions when they are subjected to pressure in the mechanical grinders in the incineration plants, which is both a safety issue and causes negative environmental impacts.

In Current Road, the composition is kept the same throughout all the years, thus for 2035, as assumed for this scenario (Fig. 5b).

In Circular Road, the share of residual waste increases to 61% since the recyclable waste fractions are discarded in the correct containers due to the assumed improved sorting behavior. Even though recyclable plastic subfractions ('hard plastic packaging', 'other foil packaging' and 'PET deposit bottles') are assumed to be sorted out from the residual waste, the share of plastic is still 12%. This is due to 'other plastic' and 'sacks/bags for waste' remaining and evolving at the same rate as the total residual waste. The third largest fraction is textiles (10%) since the amount follows the residual waste development. The share of food waste decreased to 7% in 2035 compared to 22% in 2019 due to better sorting. The packaging subfraction of glass and metal is assumed to be reduced in Circular Road due to better sorting, while the subfractions of other glass and metal are kept the same as in Current Road scenario. This results in glass and metal shares of 3 and 4%. E-waste and hazardous waste are eliminated from the residual waste, implying that a 10% annual improvement in sorting is sufficient.

In Frugal Road, all waste fractions except 'sacks/bags for waste' (7%) and residual waste (93%) itself are assumed to be eliminated entirely due to waste reduction measures and better sorting awareness.

Sorting rate

The scenario analysis tool provides qualitative and quantitative information about waste distribution in the specific containers, which is one of this study's novel contributions to scientific literature. Plastic subfractions are dispersed in the MSW system. They are found in 10 different containers of which only 4 are correct, namely the paper and plastic waste container (doorstep collection) and the plastic container (drop-off collection) for household and C&I waste as shown in Fig. 6 for 2019.

The total amount of plastic waste generated in 2019 was 400 tons, out of which 295 tons ended up in the wrong containers. The container with the largest amount of plastic, also missorted, is the residual waste container, which is approximately 50% of the total plastic waste generated. This is in line with our previous findings where the analysis was done for a larger city [8], demonstrating the significant role of consumer engagement to increase circularity. The plastic disposed of in the residual waste container is sent to incineration, increasing the fossil CO_2 emissions. Measures focusing on household (source) sorting behavior can yield an improved sorting rate of plastic.

Figure 7 shows sorting rates of plastic subfractions and the Norwegian sorting rate target in the specific year for all three scenarios together with the reference year 2019.

In 2019, the sorting rate of plastic was 29%, with 'PET deposit bottles' having the highest sorting rate of 65% and 'sacks/bags for waste' having the lowest (13%). Even though PET itself (together with other recyclable plastic polymers

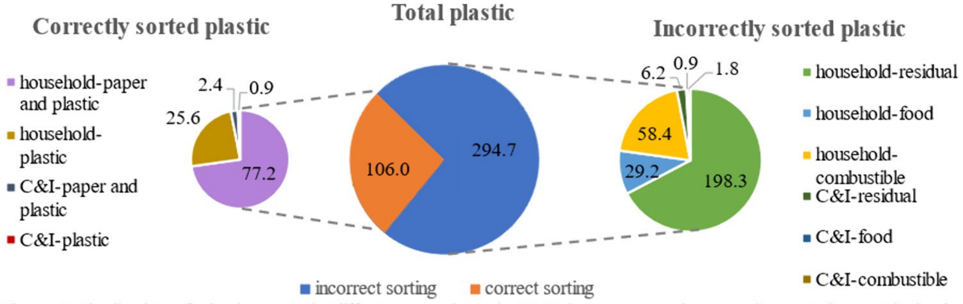


Figure 6 Distribution of plastic waste in different containers in 2019 (amounts are in tonnes), correctly sorted plastic distribution on the left, incorrectly sorted plastic distribution on the right.

Fig. 6 Distribution of plastic waste in different containers in 2019 (amounts are in tons), correctly sorted plastic distribution on the left, incorrectly sorted plastic distribution on the right

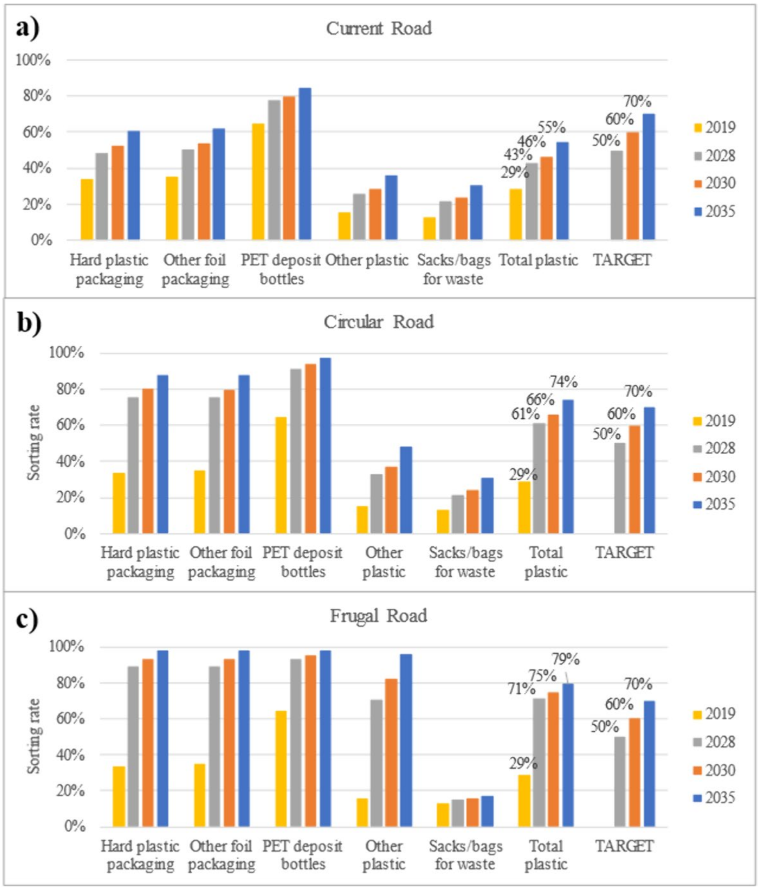


Fig. 7 Sorting rates of plastic subfractions, total plastic and sorting targets in 2019, 2028, 2030 and 2035 for Current Road (**a**), Circular Road (**b**) and Frugal Road (**c**)

such as HDPE, LDPE, PP, PS) can be discarded in the plastic waste container, meaning it is not counted as incorrect sorting in this study, there is a separate collection and recycling system for PET deposit bottles operated by a private company, thus they are not part of the MSW system and out of the scope of this study. The low sorting rate of 'sacks/bags for waste' is mainly due to their mandatory use in waste disposal at source.

'Other plastics' has the second lowest sorting rate (16%) in 2019 and can include recyclable plastic that is not packaging (plant pots), as well as unrecyclable plastic (plastic furniture). This may cause ambiguity during sorting, resulting in a lower rate of sorting, which can be improved through information and clear labelling of recyclable fractions. However, a higher sorting rate might not mean higher recycling rate since there is no information about the recyclable fraction of 'other plastics'. The subfractions 'hard plastic packaging' and 'other foil packaging' have sorting rates of 34% and 35%, and the household residual waste container contains most of the rest (see Fig. 6).

If historical trends continue, as assumed in the Current Road scenario, the scenario analysis tool estimates that sorting rates of plastic will be 43%, 46% and 55% in 2028, 2030, and 2035, respectively. The gap between the actual sorting rates and the stricter targets increases over time. Both Circular Road and Frugal Road fulfils the sorting rate targets for all three years, but the latter has a higher sorting rate than the former for total plastic (Fig. 7b–c). The same applies for all subfractions except for 'bags/sacks for waste', as the rate of change is kept the same in Circular Road (increase in sorted plastic) as in Current Road, while in Frugal Road there is no increase in sorted plastic.

Figure 8 shows the sorting rates of the food waste subfractions and the Norwegian sorting rate targets for all three scenarios in 2028, 2030, and 2035, together with the reference year 2019.

Figure 8 shows that all three sorting rate targets for food waste are fulfilled in all three scenarios, with Frugal Road having the highest sorting rates. Food waste is found in a total of 8 containers in the MSW system: food waste (the correct container), residual waste, paper and plastic waste, and combustible waste; for both households and C&I for all four containers. Similar to plastic, incorrectly sorted food waste is mainly found in the household residual waste container. Although total amounts of individual subfractions are the same in Current Road and Circular Road, which container they are discarded into differs, with an improved sorting rate (10% increase per year) in the latter

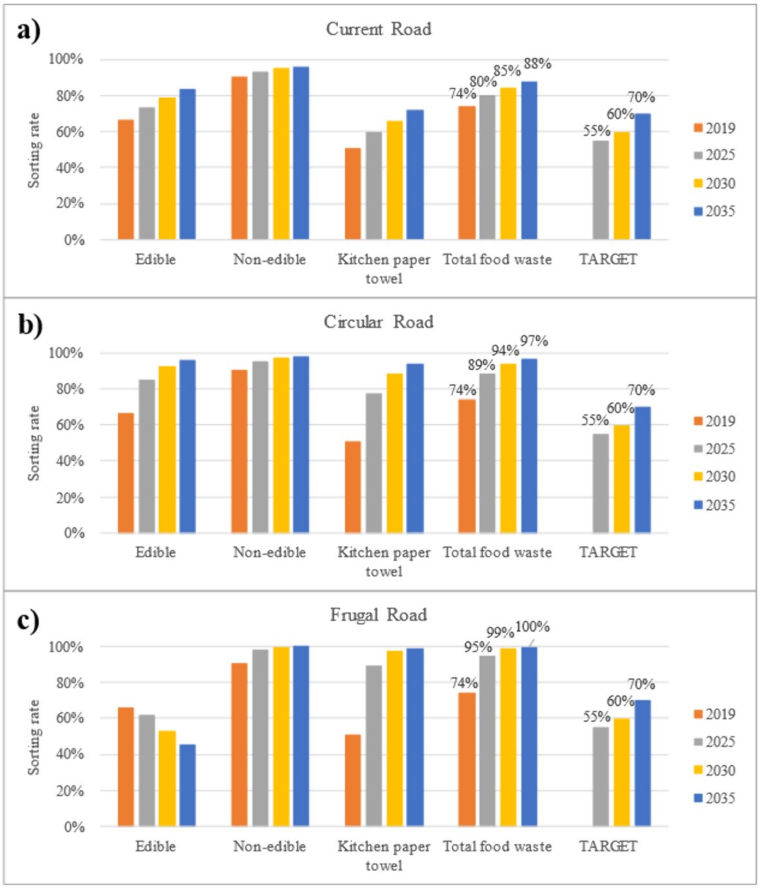


Fig. 8 Sorting rate of food waste subfractions, total food waste and sorting targets in 2019, 2028, 2030 and 2035 for Current Road (**a**), Circular Road (**b**) and Frugal Road (**c**)

scenario. In the reference year, the share of edible food waste found in the household residual waste container was 16.6% while the shares of non-edible food waste and kitchen paper towel were 2.3% and 3.2%. This resulted in a larger improvement in the sorting rate of edible food waste compared to the other two food waste subfractions for Circular Road. In Frugal Road, the edible food waste fraction is assumed to be almost entirely eliminated from the MSW system; however, rate of decrease (40%) is relative to the amount in the previous year resulting in small amount amounts left in the containers For example, 0.52 tons of edible waste is in correct containers, while 0.63 tons in incorrect containers; thus, the sorting rate becomes 45% even though total amount of edible food waste decreases to 1.15 tons in 2035 compared to 675 tons in 2019.

In summary, Frugal Road achieves better sorting rates for, and lower amounts of plastic and food waste compared to the other two scenarios, although all three scenarios fulfil the sorting targets. This shows how selective waste reduction can be more impactful than increased sorting. Therefore, measures to reach circular economy goals should also include waste reduction targets of recyclable fractions to achieve better sorting rates overall.

Recycling rate

Recycling rates are calculated for each subfraction using sorting rate and recycling efficiencies (Table 3) as given in Eq. 4. Recycling rate refers to the amount of waste that is recycled after deducing the process losses, impurities, dirt, and unrecyclable materials. Relation between recycling efficiency, sorting rate and recycling rate are illustrated in Fig. 9 for plastic subfractions and total plastic in 2019. Even

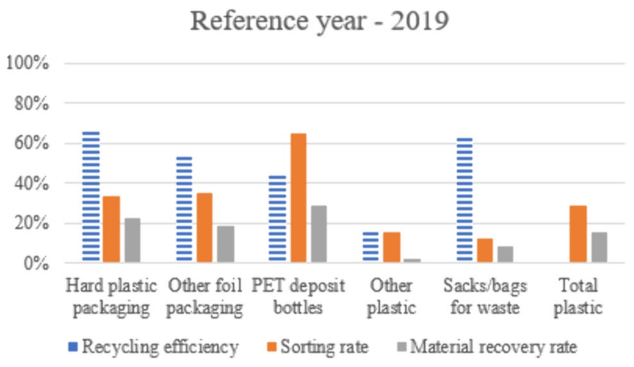


Fig. 9 Recycling efficiency, sorting rate and recycling rate of plastic subfractions and total plastic in 201911

though the recycling targets given in Table 1 apply only to plastic packaging and do not apply in Norway per today, they were considered in this study to assess the future MSW system. Norway has chosen to use sorting targets to reach the recycling targets, as domestic recycling is limited. Norwegian MSW actors are mainly responsible for handling plastic waste, giving them a potential to impact sorting rates. Fig. 10 shows recycling rates and targets for plastic.

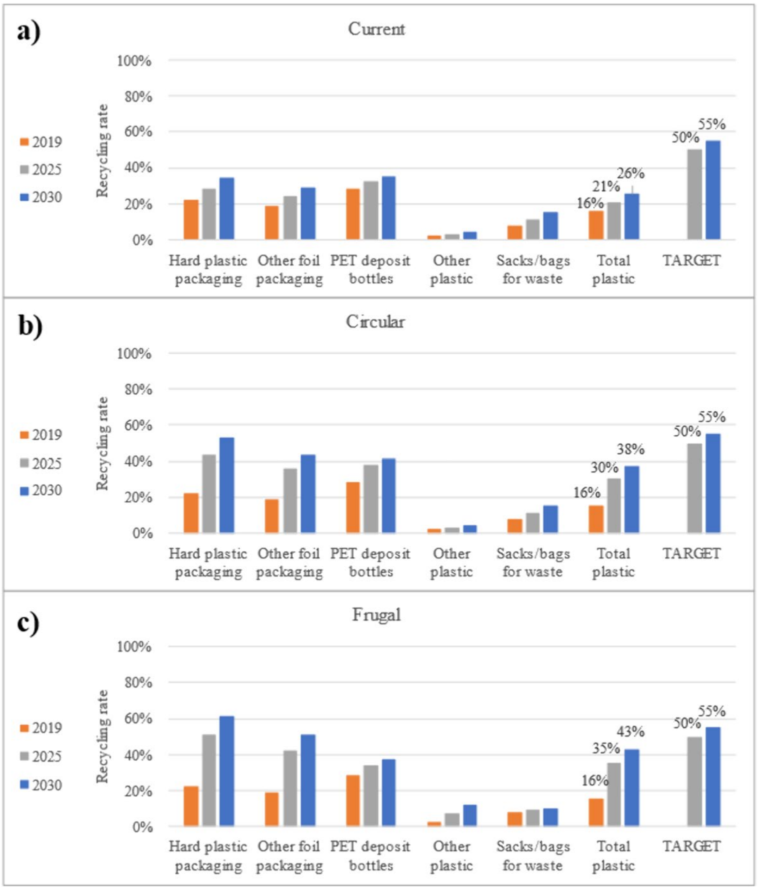
Fig. 9 shows that highest recycling efficiency of 66% that is for hard plastic packaging fraction results in the smallest losses, thus smallest difference between sorting and recycling rates. Similarly, lowest recycling efficiency of 16% belongs to other plastic that results in the largest deviation between sorting and recycling rates.

As shown in Fig. 10, in 2019 ‘PET deposit bottles’ is the plastic subfraction with the highest recycling rate, as a result of the higher sorting rate. It is followed by the 'hard plastic packaging’ and ‘other foil packaging’ subfractions with recycling rates of 22% and 19%. The latter has a higher sorting rate than the former; however, its recycling efficiency is lower, resulting in a lower recycling rate.

Recycling rate targets for plastic cannot be achieved in any of the three scenarios even though sorting rate targets are achieved. Even in Frugal Road, which has the highest recycling rate of the three scenarios, the recycling rate needs to increase by 25% until 2030. For Current Road, the recycling rate has to more than double to reach the target. This shows the importance of recycling efficiency, which is influenced by several factors. On the technology side, the recycling process determines which types of plastic and polymers can be recycled. Innovative technologies such as chemical recycling enable recycling of more plastic polymers compared to conventional mechanical recycling, thus increasing the recycling efficiency [37]. On the producer side, plastic product or packaging producers can improve the recyclability of their products by using selected plastics and limiting mixing of different polymers in one product. On the consumer side, engaging consumers for appropriate cleaning of the waste prior to disposal can improve the recycling efficiency, and there are consumer driven changes to reduce plastic waste such as banning single-use plastics.

For 2030, the targets for plastic are 60% for the sorting rate and 55% for the recycling rate. This means that if the sorting rate target is precisely met, the recycling efficiency must be at least 92%. As can be seen in Table 1, no plastic subfraction has such a high recycling efficiency at the moment; 66% is currently the highest for hard plastic packaging. Therefore, the understanding of recycling efficiency

Fig. 10 Recycling rate of plastic subfractions, total plastic and recycling target in 2019, 2025, and 2030 for Current Road (**a**), Circular Road (**b**) and Frugal Road (**c**)



is necessary to evaluate whether recycling rate targets are attainable with the existing technology combined with sorting targets.

The quantitative mapping of all waste subfractions done in this study makes it possible to calculate the recycling rate for all waste fractions and subfractions, to compare them with the respective targets (Table 1) at the right geographical resolution, the importance of which is highlighted by other researchers in the field [38]. This provides an improvement over existing calculation methods since currently packaging waste data is only available at the national level [8].

Conclusions

In this study, a scenario analysis tool was developed to assess whether the circular economy goals are attainable with the existing infrastructure and technologies, by estimating sorting and recycling rates of MSW fractions. The background data consisted of amounts in and composition of 28 waste containers containing 14 waste fractions, for both household and household-like C&I waste, as well as detailed data on 16 subfractions of 5 waste fractions (paper, glass, plastic, metal and food). This was developed by linking different data sources, to achieve a detailed description of the system. The background data was the basis to implement three scenarios: Current Road (business as usual), Circular Road (improved sorting) and Frugal Road (selective waste reduction of recyclable fractions). Amounts, sorting rates, and recycling rates were calculated for all fractions and subfractions from 2019 until 2035; however, the focus of this article was residual, food, and plastic waste. Results showed that the amount of residual waste will decrease in all three scenarios, with Frugal Road having the largest decrease of 62% by 2035. Sorting rate targets for food waste were achieved in all three scenarios. For plastic, the Norwegian sorting targets were achieved only for Circular Road and Frugal Road, while the recycling targets were not reached in any of the scenarios. This demonstrates the important role of recycling efficiency, which can be improved through proper disposal (e.g., cleanliness), technology development (e.g., sorting technology) and increased recyclability of products (design for recycling). The waste reduction strategy resulted in higher sorting and recycling rates compared to improved sorting only; however, both strategies need to be adopted to achieve circular economy goals. The main contributions of this study can be stated as:

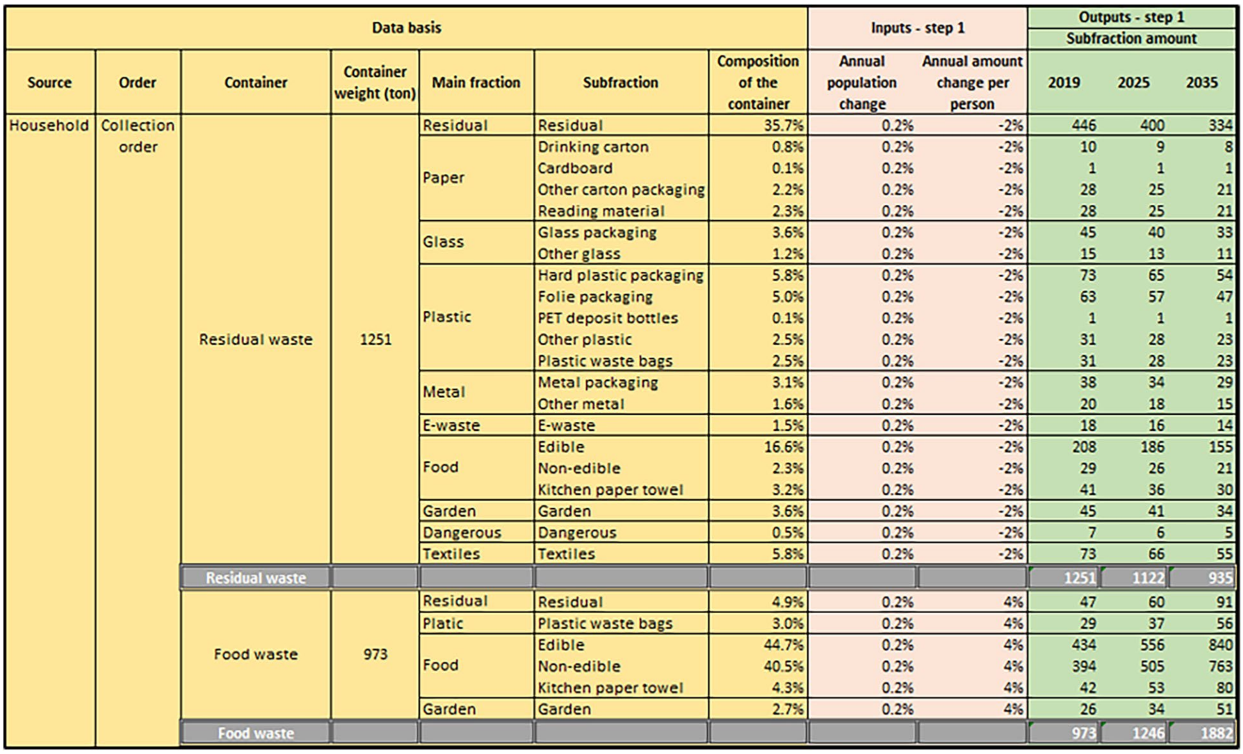
1. The linking of different sources of waste data provides a detailed description of the MSW system for a specific region, giving a new and deeper insight into how much waste is incorrectly discarded and in which containers.
2. The scenarios are targeted towards concrete circular economy goals, both sorting behavior and waste reduction strategies, as well as the recycling technology and products production perspective that are related to recycling efficiency can be implemented in the scenario analysis tool.
3. The scenario analysis tool has a high level of detail, which makes it possible to modify amounts of subfractions found in each waste container, to implement specific measures and quantify their effect on the MSW system. The tool is highly flexible and can be used for many applications.

The methodology for a detailed MSW system description can be useful for other impact assessment studies requiring waste composition data, such as LCA. We envision that the scenario development approach can be useful for policy makers to evaluate, e.g., how attainable circular economy goals are with existing infrastructure and technologies. Finally, the scenario analysis tool can be utilized to simulate the effects of different measures and changes on the waste amounts and composition, as well as technology developments on the recycling rates. This is crucial for the planning of future waste management systems. The tool can be useful to many different stakeholders, from MSW companies to policy makers, and for many different applications, from what-if scenarios to detailed assessments of which levers to pull to reach own objectives. The calculation of sorting and recycling rates provide information regarding the current circularity gap in our society. Future work can focus on improving the accuracy of the recycling efficiency with specific data on impurities, recyclable material fraction and losses in conversion process for higher precision of the scenario analysis tool.

Appendix

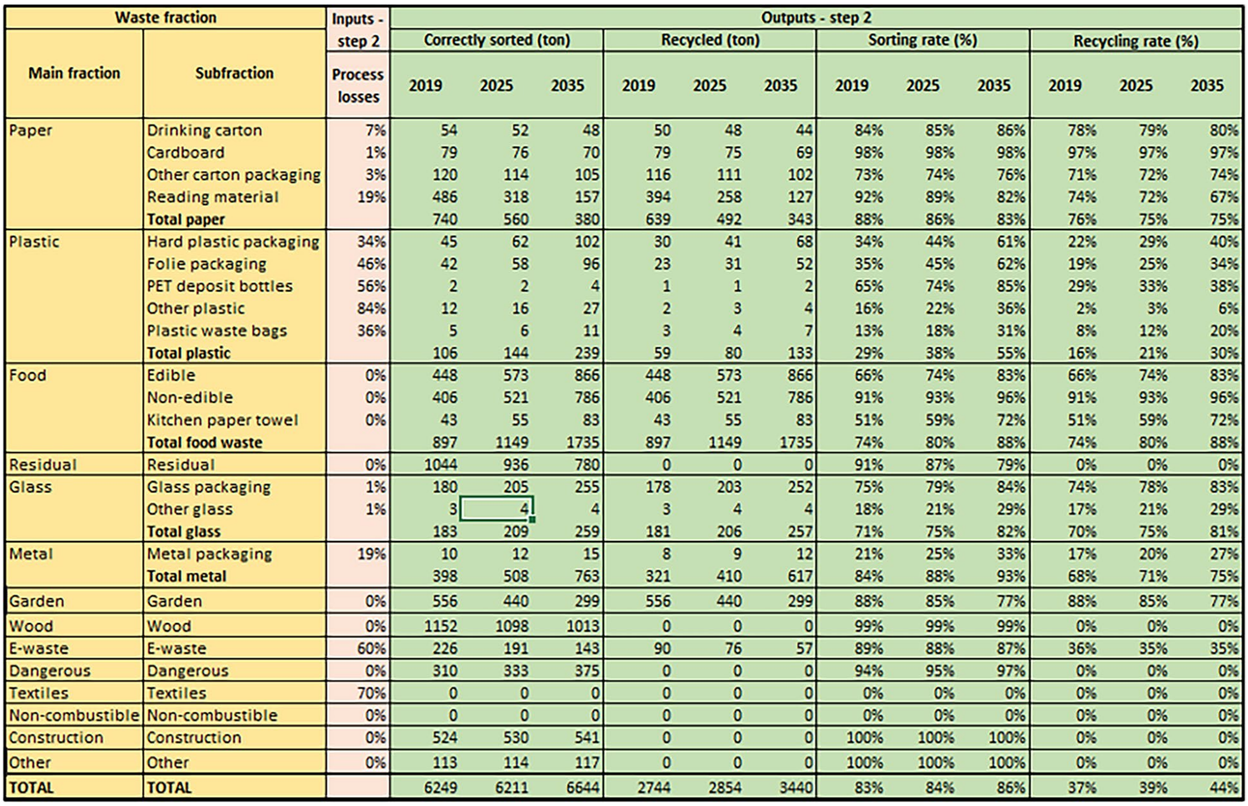
See Figs. 11, 12

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-024-01992-w.



Data basis							Inputs - step 1		Outputs - step 1 Subfraction amount		
Source	**Order**	**Container**	**Container weight (ton)**	**Main fraction**	**Subfraction**	**Composition of the container**	**Annual population change**	**Annual amount change per person**	**2019**	**2025**	**2035**
Household	Collection order	Residual waste	1251	Residual	Residual	35.7%	0.2%	-2%	446	400	334
				Paper	Drinking carton	0.8%	0.2%	-2%	10	9	8
					Cardboard	0.1%	0.2%	-2%	1	1	1
					Other carton packaging	2.2%	0.2%	-2%	28	25	21
					Reading material	2.3%	0.2%	-2%	28	25	21
				Glass	Glass packaging	3.6%	0.2%	-2%	45	40	33
					Other glass	1.2%	0.2%	-2%	15	13	11
				Plastic	Hard plastic packaging	5.8%	0.2%	-2%	73	65	54
					Folie packaging	5.0%	0.2%	-2%	63	57	47
					PET deposit bottles	0.1%	0.2%	-2%	1	1	1
					Other plastic	2.5%	0.2%	-2%	31	28	23
					Plastic waste bags	2.5%	0.2%	-2%	31	28	23
				Metal	Metal packaging	3.1%	0.2%	-2%	38	34	29
					Other metal	1.6%	0.2%	-2%	20	18	15
				E-waste	E-waste	1.5%	0.2%	-2%	18	16	14
				Food	Edible	16.6%	0.2%	-2%	208	186	155
					Non-edible	2.3%	0.2%	-2%	29	26	21
					Kitchen paper towel	3.2%	0.2%	-2%	41	36	30
				Garden	Garden	3.6%	0.2%	-2%	45	41	34
				Dangerous	Dangerous	0.5%	0.2%	-2%	7	6	5
				Textiles	Textiles	5.8%	0.2%	-2%	73	66	55
		Residual waste							1251	1122	935
		Food waste	973	Residual	Residual	4.9%	0.2%	4%	47	60	91
				Platic	Plastic waste bags	3.0%	0.2%	4%	29	37	56
				Food	Edible	44.7%	0.2%	4%	434	556	840
					Non-edible	40.5%	0.2%	4%	394	505	763
					Kitchen paper towel	4.3%	0.2%	4%	42	53	80
				Garden	Garden	2.7%	0.2%	4%	26	34	51
		Food waste							973	1246	1882

Fig. 11 Screenshot of the first step of the scenario analysis tool



Waste fraction		Inputs - step 2	Outputs - step 2											
Main fraction	**Subfraction**	**Process losses**	**Correctly sorted (ton)**			**Recycled (ton)**			**Sorting rate (%)**			**Recycling rate (%)**		
			2019	**2025**	**2035**	**2019**	**2025**	**2035**	**2019**	**2025**	**2035**	**2019**	**2025**	**2035**
Paper	Drinking carton	7%	54	52	48	50	48	44	84%	85%	86%	78%	79%	80%
	Cardboard	1%	79	76	70	79	75	69	98%	98%	98%	97%	97%	97%
	Other carton packaging	3%	120	114	105	116	111	102	73%	74%	76%	71%	72%	74%
	Reading material	19%	486	318	157	394	258	127	92%	89%	82%	74%	72%	67%
	Total paper		740	560	380	639	492	343	88%	86%	83%	76%	75%	75%
Plastic	Hard plastic packaging	34%	45	62	102	30	41	68	34%	44%	61%	22%	29%	40%
	Folie packaging	46%	42	58	96	23	31	52	35%	45%	62%	19%	25%	34%
	PET deposit bottles	56%	2	2	4	1	1	2	65%	74%	85%	29%	33%	38%
	Other plastic	84%	12	16	27	2	3	4	16%	22%	36%	2%	3%	6%
	Plastic waste bags	36%	5	6	11	3	4	7	13%	18%	31%	8%	12%	20%
	Total plastic		106	144	239	59	80	133	29%	38%	55%	16%	21%	30%
Food	Edible	0%	448	573	866	448	573	866	66%	74%	83%	66%	74%	83%
	Non-edible	0%	406	521	786	406	521	786	91%	93%	96%	91%	93%	96%
	Kitchen paper towel	0%	43	55	83	43	55	83	51%	59%	72%	51%	59%	72%
	Total food waste		897	1149	1735	897	1149	1735	74%	80%	88%	74%	80%	88%
Residual	Residual	0%	1044	936	780	0	0	0	91%	87%	79%	0%	0%	0%
Glass	Glass packaging	1%	180	205	255	178	203	252	75%	79%	84%	74%	78%	83%
	Other glass	1%	3	4	4	3	4	4	18%	21%	29%	17%	21%	29%
	Total glass		183	209	259	181	206	257	71%	75%	82%	70%	75%	81%
Metal	Metal packaging	19%	10	12	15	8	9	12	21%	25%	33%	17%	20%	27%
	Total metal		398	508	763	321	410	617	84%	88%	93%	68%	71%	75%
Garden	Garden	0%	556	440	299	556	440	299	88%	85%	77%	88%	85%	77%
Wood	Wood	0%	1152	1098	1013	0	0	0	99%	99%	99%	0%	0%	0%
E-waste	E-waste	60%	226	191	143	90	76	57	89%	88%	87%	36%	35%	35%
Dangerous	Dangerous	0%	310	333	375	0	0	0	94%	95%	97%	0%	0%	0%
Textiles	Textiles	70%	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
Non-combustible	Non-combustible	0%	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%
Construction	Construction	0%	524	530	541	0	0	0	100%	100%	100%	0%	0%	0%
Other	Other	0%	113	114	117	0	0	0	100%	100%	100%	0%	0%	0%
TOTAL	**TOTAL**		6249	6211	6644	2744	2854	3440	83%	84%	86%	37%	39%	44%

Fig. 12 Screenshot of the second step of the scenario analysis tool

Author contributions All authors contributed to the study conception and design. Conceptualization and visualization were performed by Cansu Birgen. Data curation was done by Cansu Birgen and Tuva Grytli. Supervision, project administration, and funding acquisition were done by Michael Becidan. The first draft of the manuscript was written by Cansu Birgen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available upon request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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