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RecyQMeter: Application-specific quality of recycled plastics☆

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ABSTRACT

Objectively quantifying the quality of recyclates and finding suitable applications for individual products is challenging in plastics recycling. Confronted with ambitious targets for recycled content, industry urgently needs a robust method to understand the quality of recycled plastics. This study describes the RecyQMeter tool, which was developed to address this challenge and help recyclers position their secondary materials in an appropriate market. RecyQMeter contains a first-of-its-kind extensive application-property matrix, a large dataset of application-specific material requirements obtained through data mining, expert interviews, literature searches and modeling. RecyQMeter generates a value between 0 and 1, which refers to the quality of recyclates relative to virgin plastics used in different market applications. Additionally, this tool can be used to automatically estimate substitution ratios in life cycle assessment (LCA) studies. RecyQMeter makes a significant step forward in standardizing plastics recycling and supporting decision makers in achieving higher circularity in the plastics sector with a large database, ease of use, transparent calculations, and a comprehensive approach.

1. Introduction

The European Parliament promotes the circular economy of plastics by implementing R strategies (reuse, repair, refurbish, and recycle) (Larrain et al., 2022). To date, European targets have mostly focused on quantifying plastics going to recycling or recycled content in new products. Reports and official documents often speak of targeting "high quality", but what this means in practice is rarely specified. The quality of recycled plastic depends heavily on the input waste composition and the recycling process itself (Nakatani and Hirao, 2011; Bashirgonbadi et al., 2022). Over the past few years, research has focused on achieving technical recycled quality that can meet the same characteristics as virgin plastics. This was partially achieved by mixing virgin and recycled plastics by restabilization (Pfaendner, 2022) or compatibilization (Dorigato, 2021). However, the grade and amount of virgin plastic required depend heavily on the specific application. In some cases, the technical requirements are not stringent, and compounding may not even be necessary. This is a crucial aspect, as a standardized approach—where a database with "just enough" technical requirements is established—could allow for sufficient performance to be met without significant incorporation of virgin plastic.

(Vilaplana and Karlsson, 2008) were the first to discuss the definition of quality in the context of plastic recycling. Since then, different models have been developed to quantify the quality of recycled plastics such that their values can be compared for different applications. Interfacial tension (Huysman et al., 2017), intrinsic viscosity (Rigamonti et al., 2018; Valentino, 2016), tensile strength (Gala et al., 2015), a combination of different mechanical (including tensile strength) (Gabriel et al., 2015; Demets et al., 2021; Sanabria Garcia et al., 2023) and non-mechanical properties (e.g. optical properties as well as barrier and Go/no-Go criteria for food contact requirement, coefficient of friction) (Schulte et al., 2023; Golkaram et al., 2022) have been used as components of conceptual quality in the mechanical recycling of plastics. The European Commission (EC) also presented an overarching framework in which five general aspects were distinguished in assessing technical material quality that should always be evaluated for a given

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secondary material (Caro et al., 2023). These include mechanical properties (stiffness, ductility, toughness, strength and hardness), processability (chemical stability during processing and flow behavior), aesthetical properties (odor, color, texture, and durability), chemical load (presence of intentionally [IAS] and non-intentionally added substances [NIAS]) and legal boundaries (REACH, POPs Regulations, WEEE, RoHS, and FCM Regulation) (Caro et al., 2023; Roosen et al., 2023) Aspects of these were operationalized including multi-criteria application-property decision making whereby depending on the application of the recyclates, the quality is defined by several properties, accounting for their importance via weighing factors to generate a value between 0 and 1 (Golkaram et al., 2022; Demets et al., 2021; Huysveld et al., 2022; Sanabria Garcia et al., 2023). Such application-based quality factors are particularly useful as substitution factors within the environmental impact assessment domain, such as life cycle assessment (LCA) (Rigamonti et al., 2020).

Typically, these frameworks proposed in scientific literature remain conceptual and are never translated into practically usable tools for others – academia and industry alike – to calculate with. Quality estimation requires data acquisition and several calculation steps, which may be obstacles for market actors. Therefore, a standard tool to perform such calculations is required to operationalize the models presented in the literature. The current RecyQMeter tool is the first of its kind. It models recycled quality based on a synergistic combination of the two pioneering models, namely, the Quality Model for Recycled Plastic (QMRP) (Golkaram et al., 2022) and Recyclate Quality (RQ) (Demets et al., 2021), in an efficient manner to help the producers and end-users of recycled plastics in positioning, comparing, and assessing their secondary plastics so they can select appropriate new applications, as well as to help LCA practitioners by providing guidance in applying a certain substitution factor. This tool in its current form is beneficial for quality assessment of recycled plastic (not upstream waste by the sorters, bale or shredded residues).

Whereas thhe fundamental research novelty lies in the original conception of both component models, the RecyQMeter tool provides a significant and timely further advance in the field. The two constituting models for calculation of quality were collaboratively harmonized into a unified final model by both author teams. This final model has been further developed into a practical tool that is useful for both academic and industrial applications. Its beta testing phase will enable additional validation and provide opportunities for further improvements and refinements. Moreover, for the first time, this work includes a wealth supporting data in Excel files, presenting data which is often very hard to come by, namely an extensive database of typical values for application-specific property requirements across a wide range of polymers and applications.

2. Methods

2.1. Constituting models – RQ

Published by Demets et al., the Recycling Quality (RQ) model focuses on the technical properties as the most important aspect of quality and defines two values namely: RQ^{proc} and RQ^{mech} which represent the recycling quality during the manufacture of new products (flow in the moulds) and the final material properties (mechanical properties of the recycled material). RQ^{mech} is based on quantifiable parameters such as strength (e.g., tensile strength, ISO 527), stiffness (e.g., tensile modulus, ISO 527), and impact strength (e.g., Charpy impact strength, ISO 179), which are predominant mechanical characteristics (Van Belle et al., 2020). Processability is usually determined by the flow behavior e.g., via Melt Flow Index (MFI) measured according to ISO 1133 (Demets et al., 2021).

In order to cope with the application dependency of the functionality, scoring functions were defined for each of the relevant properties per application or group of comparable applications (e.g., bottle, film, …). Depending on the severity of deviation of the recycled plastic's property to that of the application's typical virgin grades, each scoring function then returns a value between 0 and 1. Here, RQ^{proc} is defined by a scoring function f based on the relevant flow property F^{vir} (MFI or IV) of the virgin material as shown in Eq (1):

$$RQ^{proc} = f\left(F^{vir}, F^{rec}\right) \tag{1}$$

Therefore, this scoring function should produce a value close to 1 for recyclates whose MFI (or IV) value (F^{rec}) falls within the optimal processing range for the specific application. On the other hand, recycled materials that are challenging to process for this application should receive a low score, leading to a low RQ^{proc}. Materials that cannot be processed with the intended technology should receive a score of zero.

RQ_{mech} is calculated by Equation (2), by summing the scores of the essential mechanical properties P^{vir} of the virgin material, weighted by their importance for a specific application. The scoring functions evaluate how undesirable changes in each property P^{rec} are for that application, and both the scoring functions and weights are tailored to the application's requirements. For example, rigid injection molding prefers a high modulus, whereas flexible injection molding does not.

$$RQ^{mech} = \sum_{i=1}^{n} w_i . f\left(P_i^{vir}, P_i^{rec}\right) \quad \text{with} \quad \sum_{i=1}^{n} w_i = 1 \tag{2}$$

Defining scoring functions is crucial for calculating RQ factors, as they assess how well the recycled plastic's properties align with optimal values for specific applications. When designing these functions, several factors must be considered: the optimal value range, whether the property needs to match the virgin plastic exactly or just meet a threshold, and the application's tolerance for deviations. A good scoring function gives a score of 1 when the recycled plastic's property is within the optimal range and a score less than 1 when deviations reduce quality. These functions are shaped by technical data and expert input to reflect the application's sensitivity to deviations, leading to different types of functions: Trapezoidal(Scores 1 within an optimal range and decreases linearly outside it. The slope's steepness is adjusted based on the importance of the deviation.), Bell-shaped (Ideal for properties that must stay within a strict range, where deviations drastically impact functionality), Gaussian (Transitions from an optimal range to a single ideal value, useful for converters requiring precise property values), Single-sided Trapezoidal and Sigmoidal (Used when only a lower threshold is necessary. Sigmoidal functions provide a more gradual score decline compared to the linear drop in single-sided trapezoidal functions). These scoring functions are tailored to each property and application to accurately reflect quality loss due to deviations from optimal values.

2.2. Constituting models – QMRP

Quality Model for Recycled Plastic (QMRP) developed by Golkaram et al., uses aspects such as color and odor in addition to the technical properties (Golkaram et al., 2022). Thus, QMRP benefits from a larger property window which is important when the final product expects aesthetic properties and should potentially meet food contact requirements. QMRP uses a non-linear function:

$$X_i = \frac{I_{Ideal} - I_{Sample}}{I_{Min} - I_{Max}} \tag{3}$$

$$\xi_i = \frac{1}{\left(1 + |X_i|\right)^{\gamma_i}} with\ \xi_i < 1 \tag{4}$$

$$\xi_q = \prod \xi_{i=}\xi_1 \times \xi_2 \cdots$$

QMRP uses key parameters to evaluate the quality of recycled plastic by comparing its properties to ideal values. I_{Sample} represents the measured value of a specific property, such as tensile strength or impurity content, in the recycled plastic. I_{Ideal} is the ideal value for that property, typically corresponding to the virgin material's standard. I_{Max} and I_{Min} are the maximum and minimum acceptable values for the property for a specific application. X_i is a dimensionless parameter that normalizes the deviation of I_{Sample} from I_{Ideal}, enabling a standardized comparison. J_i is a weighing factor that reflects the relative importance of each property in the context of the intended application. ξ_i represents the quality of the recycled plastic concerning a single property, while ξ_q is the aggregated quality parameter that assesses the overall quality of the recycled plastic by considering all relevant properties.

QMRP applies a Go/No-GO criteria (quality equals zero outside the acceptable range for modulus; $I_{E\ modulus,\ min} = 10$ MPa $< I_{E\ modulus} < I_{E\ modulus,\ max} = 600$ MPa). This is the result of the methodology used where the individual ξ_is are added, whereas in QMRP, uses the product of ξ_i ($\xi_q = \prod \xi_i = \xi_1 \times \xi_2 \times \xi_3 \ldots$). Therefore, if one of the ξ_is equal zero, QMRP estimates zero as ξ_q.

2.3. Application properties matrix

The application property matrix refers to the multicriteria matrix in which the required properties and their typical values are listed for each application. It is based on extensive datamining of over 300 datasheets of commercial polymers, as well as expert opinions for refinement. Currently, L(L)DPE, PP, HDPE, PVC, HIPS, PET, PC and ABS are included in the database to extend it to all other meaningful commercial plastics. The application-property matrix can be found in the Supporting Information. It provides a hierarchy for users to navigate, as is shown in. for PP. The layers are as follows: 1) polymer type, 2) processing technique, 3) sector, 4) application category, and 5) (sub)application. For example, PP – injection molding – automotive – exterior parts – bumpers. Market share is used to estimate the substitution ratio based on a similar hierarchy; however, due to a lack of data, no distinction is considered between sub-applications; that is, the quality value for any sub-application is averaged and multiplied by the application (automotive) market share.

2.4. Merged and optimized model – RecyQMeter

Both constituting models RQ and QMRP were merged into the optimized calculation model RecyQMeter. Table 1 summarizes how each modeling aspect was handled in each constituting model, which version is taken over by RecyQMeter and why. Overall, QMRP tends to overestimate the quality, but improved when non-technical properties were included, showing for instance zero quality for toys. RQ provided more realistic predictions by better accounting for property deterioration. RecyQMeter followed RQ's approach but incorporated QMRP's No-Go criterion, assigning a quality of zero if any specification was unmet, ensuring stricter quality control.

Taking the best from both original methodologies, RecyQMeter uses three different groups of properties: processing properties of the material (MFI), mechanical properties of the material (tensile strength, modulus, impact strength, elongation at break, and tear strength (film only), and functional properties of the product I (oxygen transmission rate [OTR], water vapor transmission rate [WVTR], odor, sealing properties, haze, gloss, and regulatory properties).

The list of available RecyQMeter properties and their units are provided in Table 2 and A1 (Supporting Information), the latter of which also contains the relevant standards for testing. When the tool prompts the user for the inputs, it clearly specifies the units of the property.

The model works exclusively on the recyclate, being the recycled compound used to manufacture new products (potentially after blending with virgin). The input of the RecyQMeter is the measured value for the three categories of properties of recycled plastic, to the degree that they are available to the user. From this, using the product-application matrix, the application-specific scoring functions and the merged calculation model, RecyQMeter calculates the quality of the recycled plastic for different potential applications. This principle is illustrated in Fig. 2. The list is predefined in the database depending on the application. For instance, for films barrier properties and dart impact will be needed while for injection moulded objects impact strength is relevant. RecyQMeter, however, does not monitor the accuracy of the measurements and whether the properties measured follow the standards and this needs to be taken into account while using the tool (e.g. the units should match what RecyQMeter expects).

Regarding the scoring functions, RecyQMeter uses different functions depending on the property type (Supporting Information Fig. A1-6 and Table A1). Default functions depend on these properties. The user does not directly influence the choice of function. However, by choosing

Table 1
Features of the two models, QMRP and RQ, the merging and reason for the choices made.

Model feature	In RQ (Demets et al., 2021)	In QMRP (Golkaram et al., 2022)	RecyQMeter	Rationale
Model scoring function	Linear	Non-linear (exponential)	Linear	The linear function performs more accurately than the exponential function. The latter can overestimate the quality, with results concentrated in 0.7–1 region.
Assigning relative value to properties	Weighing factors	Weighing factors	Weighing factors	A weighing factor is used for each property to show the importance of that function in the quality estimation.
Go-no go criteria	Not included	Included	Included	When the value of a property is larger or lower than the acceptable range, not only the value of quality for that property but the sum of all quality values should be zero because the recyclate no longer serves the purpose.
Range of ideal values	Included	Included	Included	Essential as the quality is relative to a certain application. This range is usually similar to the value of virgin plastic properties used for specific applications.
Mechanical and not-technical properties	Not included	Included	Included	To capture all aspects of quality
Quality value estimation	Summation	Multiplication	Summation	To encompass all aspect of quality, the values of quality for each properties needs to be added or multiplied. Multiplication can underestimate the final quality value.
Database implemented	Not included	Not included	Included	A database of requirements for eight major plastics including 268 sub-applications prevents the demand for additional data collection.
User interface	Not included	Not included	Included	Previous models were based on equations which assess the quality. In practice, a user interface is developed to include the model in the background and host a large database of application-property matrix
Automatic comparison of quality across applications	Not included	Not included	Included	The tool can generate results of quality scores or filter for specific sector, tuned for the specific sector user is interested
Automatic estimation of substitution potential	Not included	Not included	Included	The tool can estimate the substitution potential for LCA studies without the need for cumbersome calculations.

Table 2
List of properties and their units implemented in RecyQMeter.

Property	Unit	Related applications
Process		
MFI	g/ 10 min	Important for processing methods like injection molding, blow molding, and extrusion to determine flow behavior.
Material		
Vicat softening temperature	^{o}C	Crucial for injection-molded parts and high-temperature applications to determine thermal stability.
Yield strength	MPa	Relevant for structural parts, films, and sheets to determine mechanical strength and elongation.
Elmendorf tear strength	g/μm	Important for films, bags, and packaging materials to evaluate tear resistance.
Dart drop impact strength	g/μm	Key for films and packaging to measure resistance to impact and puncture
Strain at break	%	Crucial for flexible films, stretch wraps, and packaging materials to ensure durability under stress.
Elastic modulus	MPa	Relevant for structural components and packaging to assess stiffness and flexibility.
Hardness D-scale	–	Used for rigid components, casings, and structural parts to measure hardness and rigidity.
Charpy impact	kJ/m^2	Relevant for structural components, automotive parts, and safety applications for impact resistance.
Product		
ESCR	h	Important for containers, bottles, and structural components exposed to chemicals and stress.
OTR	$cc/m^2/$ 24 h	Important for food and pharmaceutical packaging for oxygen barrier performance.
WVTR	$g/m^2/$ 24	Crucial for food packaging films to assess moisture barrier properties.
CoF	–	Relevant for films and packaging for handling, stacking, and machinability.
Haze	%	Important for transparent films and packaging to measure clarity and transparency.
Gloss	%	Used in packaging and consumer products for aesthetic appeal and surface finish.
Odor	–	Food packaging
Compliant to food contact regulations	Yes/No	Food packaging
Heat seal initiation temperature	^{o}C	Key for heat-sealable films in packaging applications to ensure proper sealing at the right temperature.

a property (e.g. tensile strength), the tool calls the respective function defined per property from the database. The choice of functions for individual properties are shown in Table A1.

Fig. A1-A6 in the Supporting Information show several examples of the functions used in the tool. The shape of the function is based on two factors, 1) nature of the properties and 2) the value on the X axis where quality (Y axis) is 0 or 1. The former is based on expert judgment and does not change for different applications as it is only related to the inherent characteristics of the property. For example, higher tensile strength than required, neither increase nor decreases the quality, leading to a horizontal line at larger values than ideal (Fig. A2). The beginning and end of the scoring functions are also constant across applications, while the range which is considered ideal (quality score of 1.0) varies per application.

Finally, to calculate the quality score, we use:

$$RecyQMeter\ score : \sum_{i=1}^{n} wi.fi\ , \sum_{i=1}^{n} w_i = 1 \tag{5}$$

where $f_{1,} f_{2,} f_{3,...}$ represent the scoring functions for the different properties and w_i their respective weights.

The user of the tool can choose a built-in go/no-go criterion indicating that if one of the quality scores (i.e: fx) equals zero, the RecyQMeter scores yields a zero as well no matter how well other properties perform.

The full list of weighting factors is presented in the Supporting Information. These values are based on interviews and questionnaires sent to the relevant industry experts.

2.5. Calculation of substitution ratio

The quality of recycled plastic is important in predicting the substitution ratios for LCA studies. We recommend a system expansion approach (or avoided product) in which credit is given to recycled plastic to avoid the use of virgin plastic from the market, as was originally proposed by Vadenbo et al (Vadenbo et al., 2017). RecyQMeter estimates the quality of recycled plastics for various applications. To determine the substitution ratio as a single number between 0 and 1, quality matters as well as the market or application volume to which the quality refers. For example, for a set of properties, the recyclate quality may be high for some applications such as construction but lower for others (with higher market share). Eriksen et al (Eriksen et al., 2019) divided the application groups into high-(food packaging), medium-(toys, pharmaceuticals, and electronics), and low-quality (automotive, building, and construction). Therefore, if recyclates pass the requirements of high-quality applications, they must also pass the medium- and low-quality requirements, but if they only pass the lowest-quality application, it does not avoid the share of plastics in high-quality applications. For example, food-grade PET accounts for 57 % of the PET market, whereas low-quality applications account for 43 % (Eriksen et al., 2019). Even though this approach may make sense for food packaging, dividing application requirements to high, medium and low is an oversimplification. For instance, PP trays require lower impact strength requirements than fluid tank. Huysveld et al. (Huysveld et al., 2022) define overall substitutability (OS) as functional of technical (TS) and market substitutability (MS):

$$OS = \sum_{i=1}^{n} TS_i \times MS_i \tag{2}$$

In this, TS can be calculated using the RecyQMeter score. RecyQMeter, uses the market share which is weight % of each application in the specific plastic market such as LDPE. Depending on the quality of the recycled plastic compared to each application with respective market share, recyclate can replace a virgin plastic. The logic behind this approach is that recycled plastic has a quality which is relative to the application requirements. An application such as fluid tank may have strict technical requirements (e.g. impact strength) but has low market share, while a bench might have less strict technical needs (e.g. impact strength). To allocate a fair substitutability factor, given that the recyclate may fit an application with low technical requirements but high market demand equation 2 is used. For application in LCA, following the approach from previous studies ((Huysveld et al., 2022)):

$$Net\ environmental\ impact = B - \left(S_{vm,1:1} \times TS \times MS\right) \tag{3}$$

B, the burdens of sorting, pre-treatment, recycling and post-treatment, $S_{vm,1:1}$, the savings from avoiding virgin material based on a 1:1 substitution, TS, the technical substitutability of the recycled material [0,1]; MS, the market substitutability of the recycled material [0,1].

2.6. User interface

RecyQMeter uses a user-friendly interface built in RStudio that runs on the DIAMONDS online platform. Users can request an account via https://diamonds.tno.nl/. Upon approval, users can log into and use the system. The tool is freely accessible to industry and academia, with an option for anonymous use to ensure confidentiality.

The process begins by selecting a product based on a combination of polymer type, process, sector, application, and sub-application (Fig. 1). This selection can be made interactively through a sunburst plot or a list. Users can then add preferred properties to this combination, specifying ideal values, ranges, and weights, which are stored in a database for future use. These updates are continuously informed by experts and users, creating a more comprehensive and less biased dataset. "Characterization data" allows users to enter property values from experiments on recycled plastic, and the RecyQMeter score for the final product is calculated based on these inputs. The results, including an overview of the RecyQMeter score and substitution ratios, are displayed in a bar chart.

The steps are shown in. There are parameters predefined in the tool including property related scoring function (e.g. Trapezoidal), list of plastic related properties and the equations to calculate the quality score. This tab is only visible to the administrator. The application properties includes the list of properties important for the reference application, ideal values/range for the properties and weighing factors. This tab is for the database and only administrators have access. In order to estimate the quality of recycled plastic, any user (not only administrators) should provide the list of properties measured in the lab, their values and type of plastic. This is sufficient for the quality estimation.

2.7. Limitations and assumptions

To facilitate the use of RecyQMeter for a broad spectrum of users, such as sorters, recyclers, and end-users of recyclates, several choices have been made to ensure that the tool is user-friendly.

In the plastic industry, various properties have been reported depending on the type of application and the plastic. Using the entire spectrum of properties in each application is not advisable. Therefore, RecyQMeter uses representative choices for related properties. Examples include the tensile modulus (MD and TD) and flexural modulus.

Only certain applications or processing methods are relevant to certain properties. For example, the Vicat softening temperature is used for injection molding applications, whereas the dart impact test is only relevant for films.

Despite the large database accumulated in RecyQMeter, the background data, which are mainly obtained from the technical datasheets of raw material producers, may not be comprehensive. This implies that the application requirements may be less (or more) strict than those collected from many datasheets. Thus, expert opinion matters in improving the quality of the data and ensuring that they are realistic for application demands.

Properties may be absent for a few applications due to a lack of data. RecyQMeter ignores these properties during the calculations. Importantly, if less common properties (especially those mentioned in technical datasheets) are to be used in the calculation, background data (application requirements) must be provided to ensure that the calculations are robust. This is unnecessary for properties such as tensile strength and elongation at break.

The tool uses weighting factors obtained from expert interviews, which to some degree remains subjective. This tool requires more input from its users to fine-tune the weighting factors and remove bias. Opening up the tool free-of-cost to the larger audience is intended exactly for this further refinement.

3. Case studies

3.1. Quality of recycled plastics (polyethylene, PE)

Based on the requirements of different applications of LDPE, a recycled plastic can have different quality scores. To evaluate and quantify the quality of an actual case, lab-scale recycled LDPE from printed flexible plastic packaging is chosen here as a use case, previously published by Lisiecki et al., Fig. 3 illustrates the results of five samples (description of the samples in the Supporting Information Table A2). Briefly, LDPE is pure LDPE without any coating or printing. LDPE-PU /–NC correspond to the LDPE samples with Polyurethane or nitrocellulose binder, respectively. Finally, the other two samples contain ink in addition to the binder (Table A2).

Fig. 3 shows the result of quality assessment for various applications. For application in shopping bag where yield strength is important (weighing factor 3.5), the LDPE samples show low quality value relative to LDPE-NC and LDPE-PUink. Haze showed not to be influential (weighing factor 2.5) for the quality although LDPE has better performance with respect to this property (8.5 for LDPE vs. 38.9 LDPE-PUink). For shopping bag an elastic modulus of 166–220 MPa is required. LDPE showed a value of 108.4, compared to 122.7 for LDPE-PUink. On the other hand, due to high dart drop impact (5 g/um), strain at break (671.4 %) and low haze (8.5) LDPE without ink or binder performs the

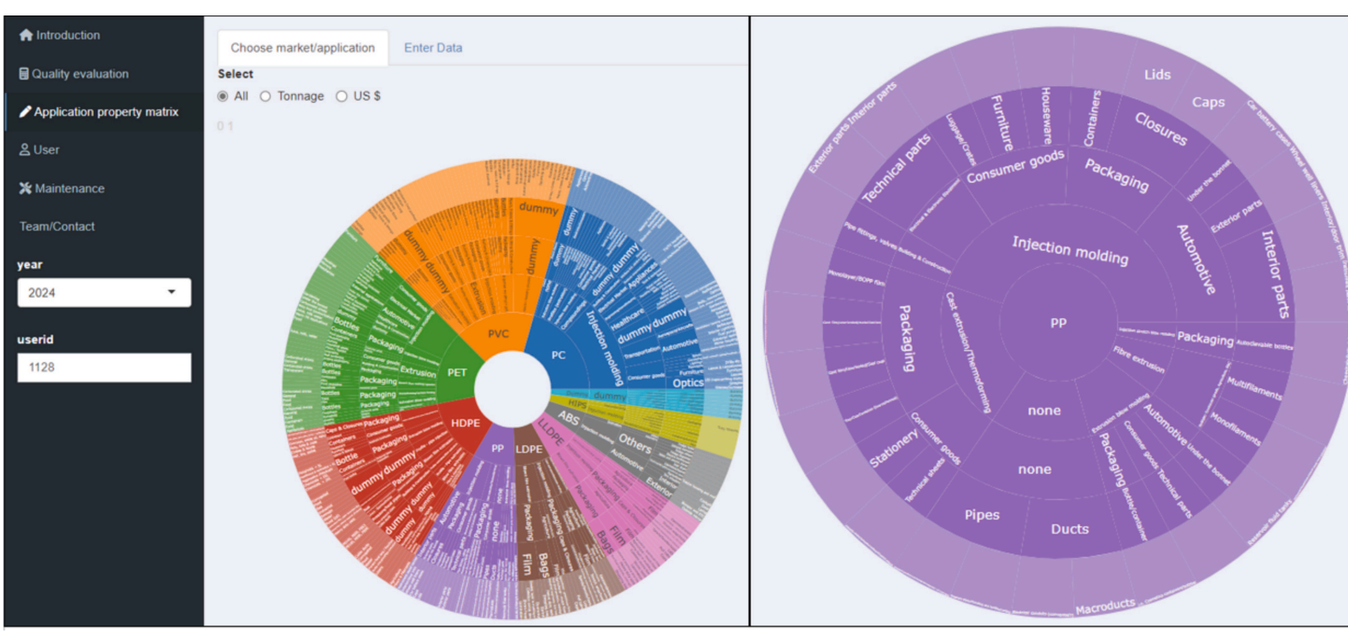

Fig. 1. The product selection steps in the RecyQMeter interface.

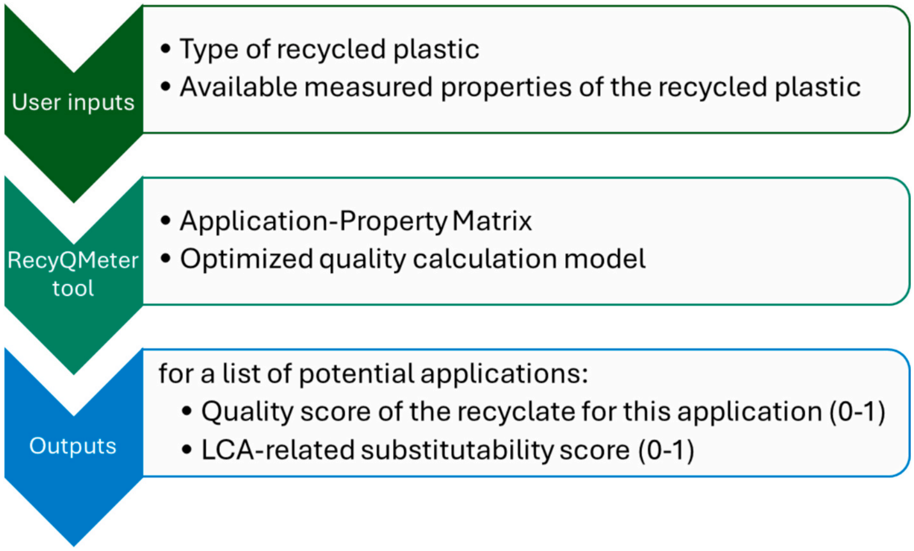

Fig. 2. Inputs and outputs of the RecyQMeter.

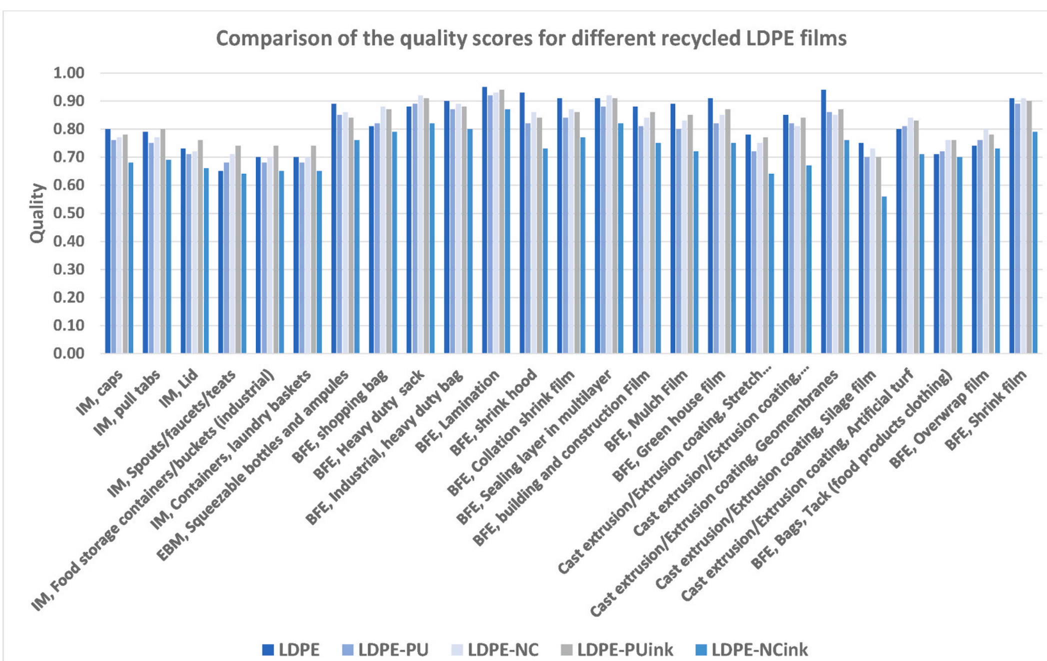

Fig. 3. Result of quality score for recycled LDPE. Data for the properties of recycled LDPE from literature (Lisiecki et al., 2024).

best (highest quality score) for other applications such as shrink film, construction, greenhouse etc.

Lisiecki et al., categorized the values of quality as follows: 1) 0.9–1 being excellent, 2) 0.8–0.9 good, 3) 0.4–0.8 suitable and 4) lower than 0.4 unsuitable. Based on this it can be seen that very few applications qualify the recyclates as excellent, while none of the recyclates are considered unsuitable. Such conclusions can be helpful in industry for strategic decisions as a tradeoff between quality and quantity exist; depending on the market demand the producers of recyclates can decide to opt for the good quality products and perhaps even incorporate virgin material or adjust processing techniques to enhance performance. Conversely, if cost reduction and higher recycling rates are prioritized, producers may focus on suitable-quality recyclates that meet the minimum requirements for specific applications. This classification system helps industries balance sustainability goals with product performance, ensuring that recycled plastics are effectively utilized without compromising functionality. Additionally, it highlights the need for continuous improvement in sorting and processing technologies to push more recyclates toward the "good" and "excellent" quality categories.

3.2. *Comparison of the result for RQ, QMRP, and RecyQMeter for ABS as the use case*

The RQ and QMRP models were compared to assess the changes in the RecyQMeter comparison. A use case (ABS) was selected based on experimental data from the literature (Scaffaro et al., 2012). The samples were characterized, and the results of one-loop reprocessing were used for this study. The data and calculations are provided in Supplementary Information. Using QMRP for only four properties (modulus, tensile strength, strain, and impact strength) led to an overestimation of the quality. This was observed in the quality result (relative to the application in consumer goods, such as phones), which was estimated to be 0.975 using QMRP. QMRP can better estimate quality if non-technical properties are included (Fig. 4). For example, by adding toy requirements (Golkaram et al., 2022), QMRP estimated the quality to be zero, showing that the material did not apply to toys even though the quality with respect to other properties was high. RQ performed better in this test, with a value of 0.787, which is more representative of recycled ABS. Although comparing the quality was difficult because there was no reference, RQ provided better predictions when the properties deteriorated. In this case, RecyQMeter used the same approach as RQ (with a quality value of 0.787); however, it used the No-Go criterion of the QMRP, where the quality was zero if the specifications were not met for one property.

4. Discussion

To assess the functionality of RecyQMeter, several cases were studied and compared with those in the literature. The mechanical and flow properties were the most commonly used among the properties used to assess recyclate quality. Gala et al., used properties such as tensile strength and calculated a quality factor of 0.83 (Gala et al., 2015). They did not provide values for the tensile strength but disclosed a 17 % reduction in the measured properties; therefore, an equivalent reduction in quality was achieved. Using RecyQMeter, a 17 % reduction in a single property, such as tensile strength, did not necessarily downgrade the material by 17 %. For example, virgin HDPE had a tensile strength of 41 MPa (see Supporting Information Fig. 7A). A 17 % reduction in tensile strength implies a strength of 35.7 MPa, which is the acceptable range for all the HDPE applications for which RecyQMeter estimates a quality of 1.0 (see Supporting Information Fig. 7A).

Compared to earlier frameworks introduced in the literature (Eriksen et al., 2019; Roosen et al., 2023), RecyQMeter benefits from 1) a comprehensive product-application matrix (Supporting Information), 2) a synergetic merging of existing models and operationalizing them into a tool, which gives it immediate potential for the recycling industry to move beyond the state-of-the-art. The plastic circularity challenge demands a robust, standardized model that is universally accepted across the value chain. The robustness comes from the fact that the tool works without additional data need for idea property values unlike other works published in the past. Moreover, what sets this model apart is its open-access availability to both academia and industry. Sector experts can update the ideal property values and their weighting factors for recycled plastics, making the tool a dynamic marketplace that connects stakeholders. Additionally, its optional integration into LCA studies helps address the long-standing ambiguity in allocating credit for recycling quality.

4.1. Value of the database (application-property matrix)

The RecyQMeter benefits from a large database of commercial polymers and a series of known applications. A list of specifications or material property requirements is included, which can be updated by the tool users upon the approval of the RecyQMeter IP owners. This is one of its attributes, as currently, the methods available in the literature may assume that material requirements are unique per plastic type. For example, the QMRP and RQ models use a similar but limited database. To apply the models to larger markets, such a database is essential to avoid the burden of collecting specifications per study. The open-access nature of the database helps users scrutinize the data, and in the case of data gaps, a network of users complements the data. Moreover, to support consistencies among studies specific standards are used in the tool for the input values. For instance, some properties such as tear strength and dart drop impact strength, depend on the thickness of the tested material. Therefore, their value is normalized by thickness to prevent inconsistencies originating from the measurements. Other properties such as WVTR can have different units, dependent on the user and their operating environment.

The granularity of RecyQMeter, in terms of the database and inputs (user interface), is an important factor missing from similar studies (Eriksen et al., 2019; Roosen et al., 2023). For example, the reported list of material properties often misrepresents application requirements. One may argue that the impact strength is important. However, the use of dart-drop impact and Elmendorf tear strength in films is more common. Roosen et al., provided a comprehensive list of technical suitability for substitution (TSS). This list comprises bottles, food trays, non-food trays, and fibers. The same was done by Eriksen et al., who divided the market into food packaging, toys, pharmaceuticals, electricity and electronics, building and construction, non-food packaging, and automotive. In contrast, RecyQMeter considers various sub-applications with different requirements that essentially change the results. For example, using RecyQMeter, the user can predict whether recycled LDPE is better suited for agricultural films or laminates.

4.2. Application in business-to-business (B2B) context

Industry requirements may vary depending on their position in the value chain. Converters (those converting granulates to final products

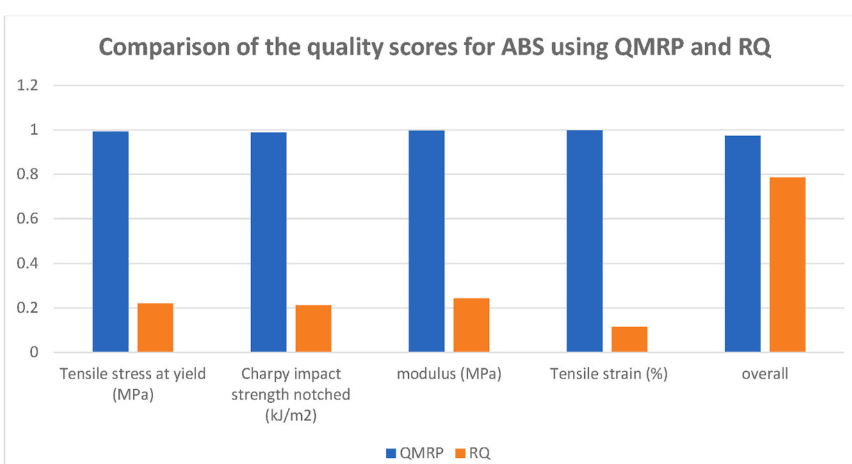

Fig. 4. Result of ABS use case to compare the QMRP and RQ models. RQ adds the individual qualities scores, while QMRP uses their product (multiplication). Higher number of properties accounted in QMRP improves the accuracy of the model while for limited number of properties QMRP overestimates the score.

such as films, bumpers, bottles) require consistent quality in their feedstock, so that the processing parameters can remain unchanged on – often highly automated – production lines. In packaging, these converters are often the brand owners themselves. They are focused on cost-effective materials that help them adhere to requirements, such as 30 % recycled content. RecyQMeter results, combined with the substitutability calculation, can identify which feedstocks are suitable for this, or even how compounders of recycled plastics should modify their formulation to make the cut.

Plastic quality standardization helps converters by ensuring consistency, reliability, and efficiency in material processing. Standardized quality parameters provide clear guidelines on properties like melt flow index, impact resistance, and contamination levels, reducing variability and production issues. This enables converters to optimize machine settings, minimize waste, and improve product performance. Additionally, standardization fosters trust in recycled plastics, making it easier to incorporate them into production without extensive testing. It also facilitates compliance with regulatory requirements and enhances supply chain transparency, ultimately leading to cost savings and more sustainable manufacturing practices.

Finally, given the open access feature of the tool, we encourage stakeholders to use RecyQMeter and provide their insights to improve the database and to verify and finetune the quality calculations.

5. Conclusions

The need for harmonization of concepts and quality scoring in the recycling sector remains a challenge. There is no one-size-fits-all solution, and the desired quality of recycled plastic varies according to the intended application. Furthermore, recyclers and converters (end users of recyclates) do not always reach an understanding. We have described the RecyQMeter tool, which was designed to facilitate decision-making by researchers and industrial experts in terms of recycling quality. The tool is based on a large database called the application-property matrix and two existing models for quality scoring. The tool uses material properties as inputs and provides the user with a value between 0 and 1 to indicate the quality of the recyclates. The quality value differs per application and thus can provide insight into the best possible end-use, accounting for all material properties, from mechanical to optical and flow indices. Finally, the market share of each application is encoded in the tool and can be used in combination with the quality value to estimate the substitution factor of recyclates, thus overcoming inconsistencies in life cycle assessment studies.

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CRediT authorship contribution statement

Milad Golkaram: Writing – original draft, Visualization, Project administration, Data curation, Conceptualization. **Ruben Demets:** Data curation. **Jack T.W.E. Vogels:** Software. **Jan Harm Urbanus:** Methodology. **Amalia Christoula:** Data curation. **Raphael Elbing:** Software. **Steven De Meester:** Investigation, Conceptualization. **Kim Ragaert:** Project administration, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.114846.

Data availability

Data will be made available on request.

References

Bashirgonbadi, A., Saputra Lase, I., Delva, L., Van Geem, K.M., De Meester, S., Ragaert, K., 2022. Quality evaluation and economic assessment of an improved mechanical recycling process for post-consumer flexible plastics. Waste Manag. 153, 41–51. https://www.sciencedirect.com/science/article/pii/S0956053X22004275.

Belle, Van, A., Demets, R., Mys, N., Van Kets, K., Dewulf, J., Van Geem, K., De Meester, S., Ragaert, K., 2020. Microstructural contributions of different polyolefins to the deformation mechanisms of their binary blends. Polymers.

Caro, D., Albizzati, P.F., Cristobal Garcia, J., Irdanto, S.L., Pelayo, G.G., Roeland, J., Elena, G., et al., 2023. Towards a better definition and calculation of recycling. Publications Office of the European Union, Luxembourg (Luxembourg).

Demets, R., Van Kets, K., Huysveld, S., Dewulf, J., De Meester, S., Ragaert, K., 2021. Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics. Resour. Conserv. Recycl. 174, 105826. https://www.sciencedirect.com/science/article/pii/S0921344921004353.

Dorigato, A., 2021. Recycling of polymer blends. Adv. Ind. Eng. Polym. Res. 4 (2), 53–69. https://www.sciencedirect.com/science/article/pii/S2542504821000130.

Eriksen, M.K., Damgaard, A., Boldrin, A., Astrup, T.F., 2019. Quality assessment and circularity potential of recovery systems for household plastic waste. J. Ind. Ecol. 23 (1), 156–168. https://doi.org/10.1111/jiec.12822.

Gabriel, D., Soemardi, T., Zagloel, Y., Kiswanto, G., 2015. Recycled plastic quality indicator development using material testing results and radar chart. Adv. Mat. Res. 1119, 821–827.

Gala, A.B., Raugei, M., Fullana-i-Palmer, P., 2015. Introducing a new method for calculating the environmental credits of end-of-life material recovery in attributional LCA. Int. J. Life Cycle Assess. 20 (5), 645–654. https://doi.org/10.1007/s11367-015-0861-3.

Golkaram, M., Mehta, R., Taveau, M., Schwarz, A., Gankema, H., Urbanus, J.H., De Simon, L., Cakir-Benthem, S., van Harmelen, T., 2022. Quality model for recycled plastics (QMRP): An indicator for holistic and consistent quality assessment of recycled plastics using product functionality and material properties. J. Clean. Prod. 132311. https://www.sciencedirect.com/science/article/pii/S0959652622019151.

Huysman, S., Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S., 2017. Performance indicators for a circular economy: A case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54.

Huysveld, S., Ragaert, K., Demets, R., Nhu, T.T., Civancik-Uslu, D., Kusenberg, M., Van Geem, K.M., De Meester, S., Dewulf, J., 2022. Technical and market substitutability of recycled materials: Calculating the environmental benefits of mechanical and chemical recycling of plastic packaging waste. Waste Manage. 152, 69–79. https://www.sciencedirect.com/science/article/pii/S0956053X22004081.

Larrain, M., Billen, P., Van Passel, S., 2022. The effect of plastic packaging recycling policy interventions as a complement to extended producer responsibility schemes: A partial equilibrium model. Waste Manag. 153, 355–366. https://www.sciencedirect.com/science/article/pii/S0956053X22004573.

Lisiecki, M., Belé, T.G.A., Ügdüler, S., Fiorio, R., Astrup, T.F., De Meester, S., Ragaert, K., 2024. Mechanical recycling of printed flexible plastic packaging: The role of binders and pigments. J. Hazard. Mater. 472, 134375. https://www.sciencedirect.com/science/article/pii/S0304389424009543.

Nakatani, J., Hirao, M., 2011. Multicriteria design of plastic recycling based on quality information and environmental impacts. J. Ind. Ecol. 15 (2), 228–244. https://doi.org/10.1111/j.1530-9290.2010.00316.x.

Pfaendner, R., 2022. Restabilization – 30 years of research for quality improvement of recycled plastics review. Polym. Degrad. Stab. 203, 110082. https://www.sciencedirect.com/science/article/pii/S0141391022002609.

Rigamonti, L., Niero, M., Haupt, M., Grosso, M., Judl, J., 2018. Recycling processes and quality of secondary materials: Food for thought for waste-management-oriented life cycle assessment studies. Waste Manag. 76.

Rigamonti, L., Taelman, S.E., Huysveld, S., Sfez, S., Ragaert, K., Dewulf, J., 2020. A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. Waste Manag. 114, 331–340. https://www.sciencedirect.com/science/article/pii/S0956053X20303810.

Roosen, M., Tonini, D., Albizzati, P.F., Caro, D., Cristóbal, J., Lase, I.S., Ragaert, K., Dumoulin, A., De Meester, S., 2023. Operational framework to quantify "quality of recycling" across different material types. Environ. Sci. Tech. 57 (36), 13669–13680. https://doi.org/10.1021/acs.est.3c03023.

Sanabria Garcia, E., Huysveld, S., Nhu, T.T., De Meester, S., Dewulf, J., 2023. Technical substitutability of recycled materials in life cycle Assessment: A comprehensive review and framework for quantification. Waste Manag. 171, 324–336. https://www.sciencedirect.com/science/article/pii/S0956053X23005482.

Scaffaro, R., Botta, L., Di Benedetto, G., 2012. Physical properties of virgin-recycled ABS blends: Effect of post-consumer content and of reprocessing cycles. Eur. Polym. J. 48 (3), 637–648. https://www.sciencedirect.com/science/article/pii/S0014305712000213.

Schulte, A., Velarde, P.Á.S., Marbach, L., Mörbitz, P., 2023. Measuring the circularity potential of recycled LDPE based on quantity and quality conservation - a functional requirement matrix approach. Resour. Conserv. Recyl. Adv. 17, 200127. https://www.sciencedirect.com/science/article/pii/S2667378922000645.

Vadenbo, C., Hellweg, S., Astrup, T.F., 2017. Let's be clear(er) about substitution: a reporting framework to account for product displacement in life cycle assessment. J. Ind. Ecol. 21 (5), 1078–1089. https://doi.org/10.1111/jiec.12519.

Valentino, G., 2016. Life Cycle Assessment of PET bottles: closed and open loop recycling in Denmark and Lombardy region. https://www.politesi.polimi.it/bitstream/10589/136151/3/2017_10_Valentino.pdf.

Vilaplana, F., Karlsson, S., 2008. Quality concepts for the improved use of recycled polymeric materials: a review. Macromol. Mater. Eng. 293 (4), 274–297. https://doi.org/10.1002/mame.200700393.