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Plastics Recycling with Tracer-Based-Sorting: Challenges of a Potential Radical Technology

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Abstract: To improve the recycling quality of plastics packaging and achieve high recycling rates new identification and sorting technologies are required. Tracer-based-sorting (TBS) is an innovative identification technology based on fluorescent tracers and a corresponding detection unit. TBS can be considered a radical technology change towards a circular economy for plastics and to support sustainability as it has the potential to render several established sorting and/or recycling steps obsolete. This article shows which drivers and barriers are perceived by stakeholders with regard to the implementation of TBS in the market and how challenges are addressed responsibly in the early phases of the innovation process. Influencing external factors and framework conditions of TBS are identified and suitable business models for TBS in a circular economy are discussed. Further, practical recommendations on how to optimize technology and market development for TBS are provided. To obtain these results a mixed method approach of integrated innovation and sustainability analysis, external environment analysis (PESTEL analysis), and business model development approaches was chosen. The research results can be understood as a practical contribution towards a responsible and sustainable implementation of a radical technology-based innovation for a circular economy of plastics.

Keywords: tracer-based-sorting; sorting and pretreatment; mechanical recycling; plastics packaging; implications for plastics recycling; circular economy; plastic value chains; technology innovation; sustainable business models

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1. Introduction

Increasing environmental awareness and the urgent need to tackle climate change has led to a higher visibility of environmental concerns and related social aspects in society. There is a high media attention to the effect of plastics in nature and to other, more regional environmental issues. Intensive political stipulations by the younger generation in the "Fridays for Future" initiative (see https://fridaysforfuture.org/, accessed 24 November 2020) and the increased considerations of the United Nations' sustainable development goals (SDGs) (see https://sustainabledevelopment.un.org/sdgs, accessed 24 November 2020) are also strong drivers of environmental changes. Thus, sustainable development with all its aspects has become important for government and industry [1]. A major part of global solid waste consists of plastics [2]. Some of this plastic waste, if not handled properly, enters the environment with potential contamination of soil and water including the oceans [3]. On a global scale, approximately 360 million tons of plastic are produced per year; an assumed 5 to 13 million tons of this enter the ocean [4]. Amongst others, the European Union has started initiatives to foster a circular economy [5] and has adopted a plastics strategy [6].

In this context, packaging plays an important role, as the packaging industry in Europe consumes about 40% of all polymers [7]: most products and goods require packaging amongst others in order to provide, protect and conserve a product, or to provide marketing, advertising and information functions [5]. In Germany, specific laws on packaging and recycling regulate how packaging has to be dealt with [8,9]. Besides the avoidance and reuse strategy, there is a strong emphasis on improved plastics recycling, particularly for plastics packaging. Similar legislation exists in other European countries, implementing European law.

Post-consumer packaging waste is a very heterogeneous waste stream. In order to retrieve valuable material after collection, it has to be sorted, cleaned and regranulated or processed otherwise in order to gain material which can be used for producing new packaging (or other products). State of the art sorting requires large scale plants which rely on separation technologies such magnetic separators (for ferrous metals), eddy current separators (for non-ferrous metals), screening drums (for generation of defined particle size as a pre-treatment for subsequent separation steps) and near infrared (NIR)-based separation techniques (for main polymer groups) [10,11]. In this context, NIR plays an important role [12]: in modern sorting plants it is used to identify materials of components in a pre-sorted packaging waste stream which can then be mechanically separated accordingly [13]. These technologies are using the inherent packaging material properties (such as conductivity or irradiation absorption) as sorting criterion. Consequently, all existing traditional separating technologies are limited to these material properties. Up to now, typical industrial sorting facilities produce about 16–20 single sorting fractions (e.g., the four main polymers PP (Polypropylene), PE (Polyethylene), PET (Polyethylene terephthalate), PS (Polystyrene); paper; aluminum; etc.). Each fraction requires more or less a specific recycling route [14]. Differentiation of identical packaging materials used for different purposes (e.g., food- or non-food application) is not possible. Moreover, recyclates often have a lower quality than virgin material. Only 9% of all plastics ever produced have been recycled, and only 10% of this proportion have been recycled more than once [15].

In order to improve recycling of plastics packaging and achieve high recycling rates as required by law and stipulated by the public, novel approaches to deal with plastics packaging waste are required [16]. To this end, fluorescent tracers can be used in combination with image recognition to achieve an improved identification and sorting of packaging waste. Of the several existing approaches, the new technology tracer-based-sorting (TBS) can be seen as particularly efficient and robust [17–20]. TBS uses fluorescent tracer materials and a corresponding detection unit as basis for sorting plastics waste [17,18]. The fluorescent tracer acts as a defined means of identification customized to the packaging use or to identify the intended recycling route (see Figure 1 for schematic diagram). This identification is not related to the inherent material properties [19]. Thus, TBS offers an efficient and reliable process to identify packaging and for other products with the potential to improve plastic waste sorting and recycling.

However, implementing the concept in practice will lead to major changes of technology and market. In contrast to a typical buyer/seller-technology, TBS is characterized by a multitude of interlinked actors who have to be managed, and their actions have to be harmonized [20]. Recycling is a thriving business relying on a complex value chain involving different stakeholders such as waste management companies, recyclers, brand owners, producers of packaging and packaging materials, producers of (recycled and virgin) polymers, compounders, trade, and politics. Additionally, recycling is strongly influenced by legislation. The current political discussion is guided by the ideal of a circular economy based on closing material loops and might lead to further regulations fostering waste avoidance, recycling and increased use of recyclates in plastics packaging production. This serves as an important driver for implementation of new identification and sorting technologies.

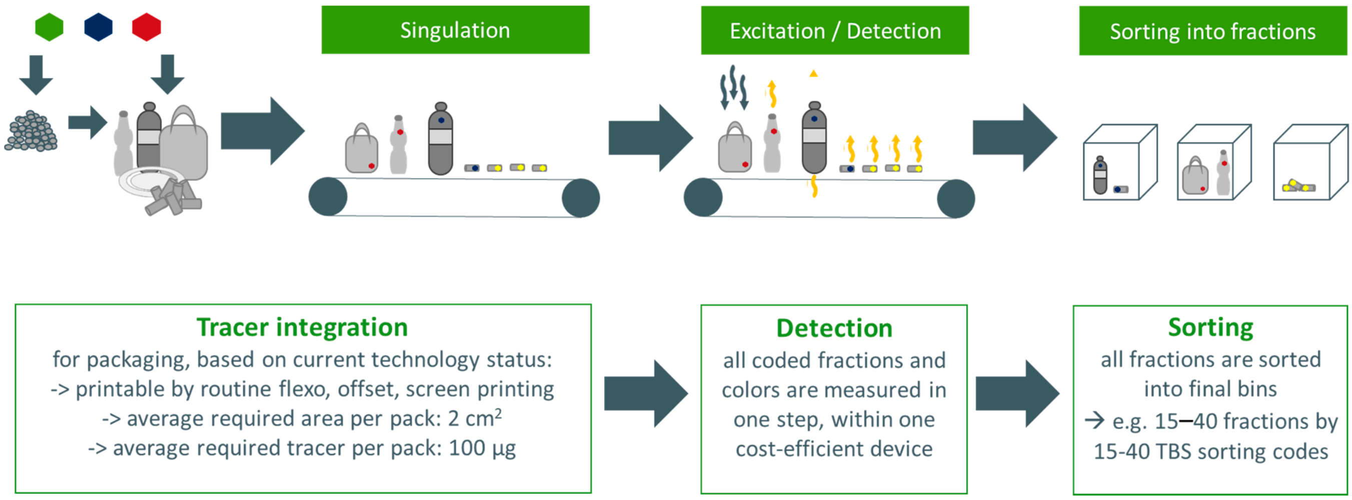

Figure 1. Functional principle of tracer-based-sorting (TBS) for identification and sorting of plastic packaging (source: Jochen Moesslein, Polysecure GmbH).

When a successful technology implementation leads to a shift in power within the market, a technology can be considered disruptive [21]. The introduction of the term "disruptive innovation" or "disruptive technology" is mainly attributed to Christensen [22,23]. Disruptive innovations are often enabled or fueled by radical technological developments. TBS can be considered a radical technology change for plastics recycling as it has the potential to render several sorting and/or recycling steps obsolete. The combination of tracer (applied at packaging production) and detection unit (applied at sorting/recycling stage) can lead to business model innovations. One objective of the research project MaReK [17] is, among others, to develop a sustainable business model for TBS. A sustainable business model (SBM) does not only create competitive advantage, but also "contributes to a sustainable development of the company and society" [24]. As such, SBMs can be seen as important drivers for innovation for sustainability in companies [25–27]. Circular economy business models can be understood as a subcategory of SBMs and can "help to prolong lifetimes of products and parts through successive cycles of reuse, repair, remanufacturing and closing material loops" [28]. Hence, SBMs have the potential to contribute substantially to a circular economy.

In this article, the following two research questions are addressed: What are the challenges of implementing tracer-based-sorting, a radical technology-based innovation for a plastics circular economy, into the market? How are these challenges addressed responsibly to achieve a more sustainable solution for plastics sorting and recycling?

This study is part of the research project MaReK ("Tracer-based sorting and recycling system for plastic packaging"), a collaborative project with several industry and research project partners, funded by the German Federal Ministry of Education and Research (see www.hs-pforzheim.de/marek). It was conducted as action research [29], i.e., the authors were embedded in the research project to support technology development and to prepare commercialization.

As TBS can be considered a technology still in a development stage (a TBS identification plant prototype is currently available), we developed a mixed method approach that provides information about how to identify and how to address challenges of implementing this potentially radical technology.

2. Materials and Methods

To address the research questions, a method mix is used as shown in Figure 2 and explained in more detail below.

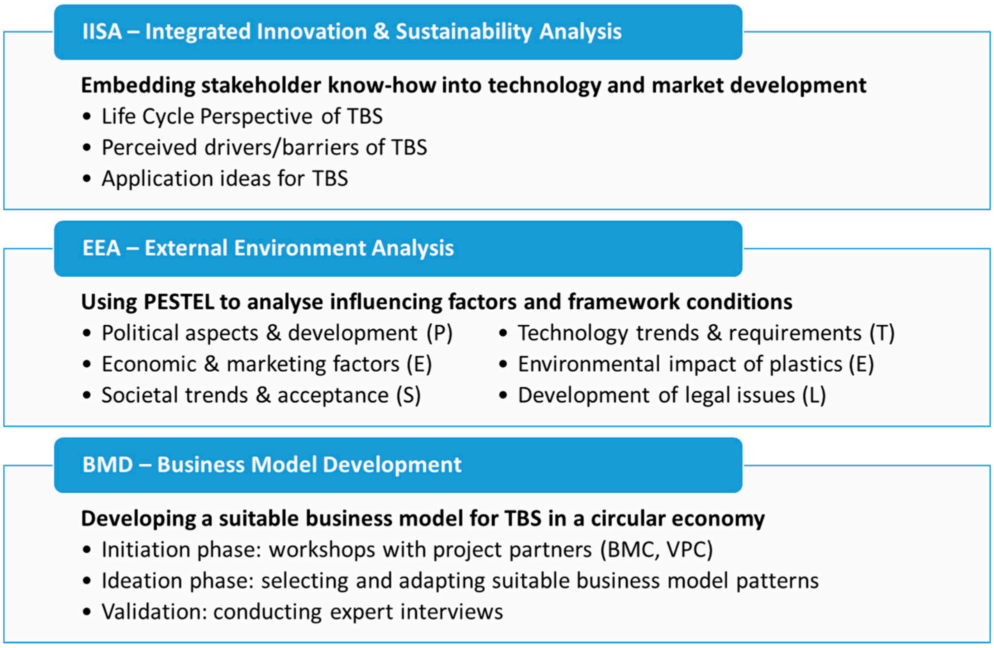

Figure 2. Methods used to address the research questions of this paper. Own illustration.

2.1. *Integrated Innovation and Sustainability Analysis for New Technologies (IISA)*

The methodological approach of the IISA [30] consists of two main elements: stakeholder inclusion in three successive steps (analysis, dialogue, integration, also see [31–33]) and sustainability assessment of the innovation at an early stage (also see [31–33]). Primary stakeholders (within the value chain of plastic packaging) and secondary stakeholders (from legislation, state agencies, governments and NGO) are involved. For the purpose of this research IISA was applied in the MaReK project to (i) gain a first overview of perceived drivers and barriers and possible environmental impact, (ii) and to elaborate and discuss first (in part still vague) application ideas for the TBS sorting technology. The IISA approach was applied as follows:

1. Life cycle perspective of TBS: A holistic view on the life cycle of plastic packaging was provided based on a stakeholder analysis: Stakeholders were identified and the potential impact on them by the new technology was assessed—a stakeholder with a high potential impact and/or affectedness was then rated as "relevant".
2. Perceived drivers/barriers of TBS: Workshops were chosen as the appropriate means to gain insights on perceived drivers and barriers of TBS from the viewpoint of stakeholders. Two stakeholder workshops on the TBS were organized, one in September 2018 and another one in September 2019. Both workshops had the same organizational procedure (technology introduction and explanation, technology demonstration, working groups) and similar participation in terms of stakeholder categories. In the first workshop, participants wrote down perceived drivers and barriers of TBS and clustered them into different categories. Each participant then rated the most important driver and barrier category. In the second workshop, driver and barrier categories collected during the first workshop were presented to the new participants, who then again rated the importance of these categories.
3. Application ideas for TBS: The second stakeholder workshop was also used to include stakeholder know-how into initial application ideas for TBS. First, the approximately 40 external participants, some of them international guests, had the opportunity to view the prototype of the TBS packaging waste sorting machine. They were briefly informed about the MaReK project and the TBS technology. Subsequently, participants were divided into four moderated groups, each with 8–10 participants. Each group was given the title of an application idea to work with. In a 90-min

session, each group discussed (i) ideas for practical implementation, (ii) relevant actors, structures, and measures for implementation, and (iii) specific drivers and barriers for the TBS application idea. After a short break, the results were shown to all participants, who then rated the potential for each TBS application idea in a portfolio by assessing its feasibility and attractiveness.

The sustainability assessment of TBS was carried out parallel to these steps in a detailed analysis. The energy and material flows of a conventional system for lightweight packaging sorting and recycling (and two other options including TBS) were analyzed and implemented into a virtual material flow model. Based on this model we conducted a life cycle assessment (LCA) to evaluate the potential environmental impact of the conventional system and alternative options including TBS. However, the results will be published separately and are not in the focus of this paper.

2.2. External Environment Analysis (EEA)

The strategic management tool PESTEL is used to analyze the external business environment. Influencing external factors and framework conditions are identified and classified in one of six categories: Political (P), Economic (E), Social (S), Technological (T), Environmental (E), and Legal (L) [34]. For this purpose, relevant literature and other publications of the past five years in the areas of recycling, packaging and circular economy were reviewed. Sources comprised scientific studies, reports of political initiatives, industry initiatives and associations, NGOs, media information and company reports. Research categories are shown in Table 1. The results of the EEA are used to derive recommendations for action with respect to market and technology development. Additionally, strategic options on how the boundary conditions should be changed (by addressing political, social and regulatory actors) are shown.

Table 1. Research categories for external environment analysis (EEA).

PESTEL Category	Research Subject
POLITICAL	Flanking political aspects regarding trends in Circular Economy, plastics recycling and packaging.
ECONOMIC	General market conditions and economic factors in waste management, plastics recycling, and packaging, business model trends.
SOCIO-CULTURAL	Social framework conditions and questions of acceptance by citizens and other actors.
TECHNOLOGICAL	Technology trends and needs in plastics recycling and packaging, development of new and/or competing technologies.
ENVIRONMENTAL	Interaction with the environment or environmental impact related to plastic packaging, plastic waste and recycling.
LEGAL	Development of legal issues (federal, state, EU) related to plastic packaging, recycling and circular economy.

Source: Adapted from [34].

2.3. Business Model Development (BMD)

To develop suitable business models for TBS in a circular economy, a multi-step procedure was applied [35]:

- Initiation phase: First business models were developed in a workshop with project partners using value proposition and business model canvases taking basic circular economy principles into account.
- Ideation phase: suitable business model patterns from the literature were selected and adapted.
- Validation: value proposition and selected business model patterns were validated by conducting 8 expert interviews (five brand-owner companies and three waste management companies)

This led to first business model concepts as a basis for further commercialization activities.

3. Results

3.1. Results of Applying the IISA Approach

3.1.1. Stakeholders in a Life Cycle Perspective

Based on the stakeholder analysis, the following stakeholders were assessed as relevant for further participation in the stakeholder dialogue: technology provider, brand owners/producers, packaging producers, recycling businesses, waste management companies, dual systems, education and research, as well as authorities and legislators. Their classification in the life cycle of packaging is shown in Figure 3.

3.1.2. Innovation Drivers and Barriers of TBS

All six superordinate stakeholder groups (see caption in Figure 3) were represented by participants in both workshops. Members of the MaReK project consortium acted as moderators and observers. The results of the discussion in working groups were summarized in ten driver clusters and nine barrier clusters. In both workshops, all participants qualitatively assessed the importance of driver and barrier clusters. This also shows an indication of how certain driver and barrier clusters developed over time. High recyclate quality is the predominant driver category, while the potential of TBS in handling packaging complexity and as a marketing opportunity appears to be increasingly important (see Figure 4). Concerning the challenges towards the implementation of TBS, there is no overriding barrier category. The barriers comprise mostly legal issues (regulatory framework & quality/safety) or economic concerns (profitability and distribution of efforts/benefits) (see Figure 5).

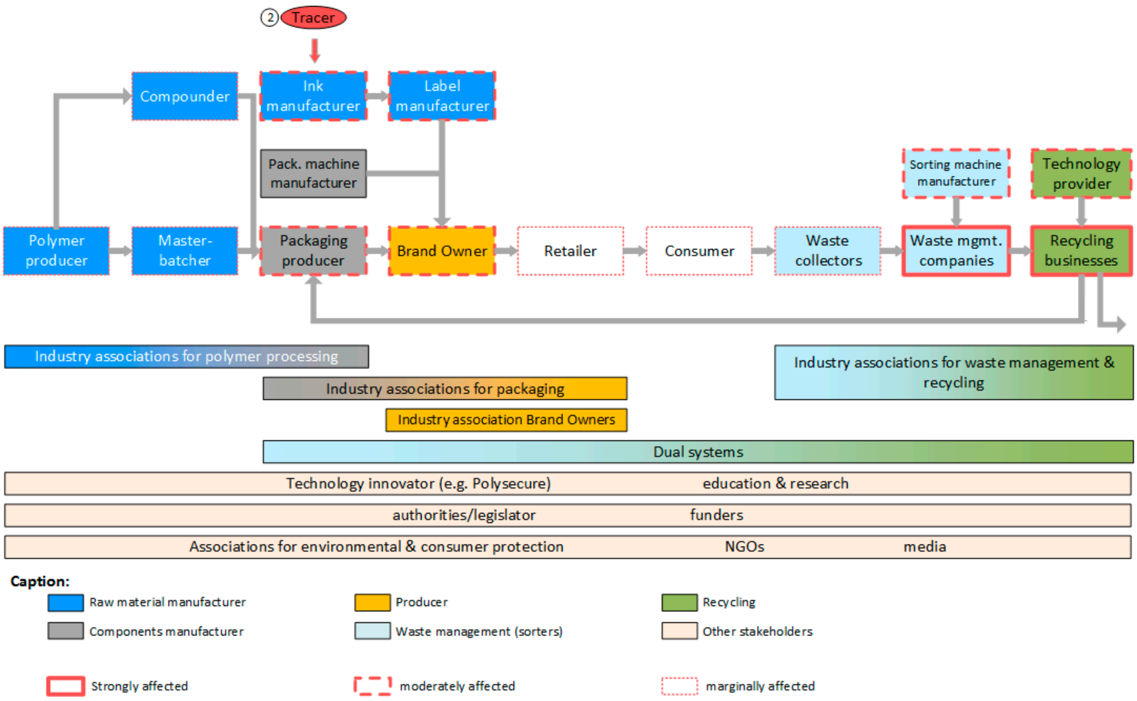

Figure 3. Stakeholders within the life cycle perspective of plastic packaging (with TBS). Adapted from [36].

3.1.3. Evaluating the Potential of Four TBS Application Ideas

In the following, the results of the moderated working groups in the second MaReK stakeholder workshop are briefly presented. Four potential TBS application ideas were developed and discussed:

1. TBS for separating food and non-food packaging material flows
    - Either food grade or non-food grade material receives a TBS tracer.
    - This enables specific food grade recycling routes for PP, PE or PET.

- Involving regulatory bodies is crucial, these are decisive forces here (German packaging law [8], EU regulation REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), see [37]).

2. TBS for separating brand- or manufacturer-specific packaging
   - Getting well-known high-quality recyclates back, marketing aspects ("closing the loop")
   - Percentage of mass is a critical issue, doubts of profitability for sorters/recyclers in small waste systems.
   - Involving brands, recyclers, packaging associations, whereas government provides framework.
3. TBS to provide high-purity recyclates ("marking for special recycling")
   - Marking packaging with special recycling routes (black polymers, separable multilayer, washable inks, etc.).
   - Compatible with existing sorting and recycling processes in advanced waste management systems (i.e., in Germany).
   - Structures like collaborative initiatives of relevant companies and associations are important (CEFLEX—a European consortium of companies on flexible packaging, see https://ceflex.eu/), roundtable of the German Federal Ministry for the Environment).
4. TBS to provide high-purity recyclates ("bottle-2-bottle recycling")
   - Enhancing and improving bottle-2-bottle recycling.
   - Separating specifically according to bottle contents (water, non-water, carbonated soft drinks).

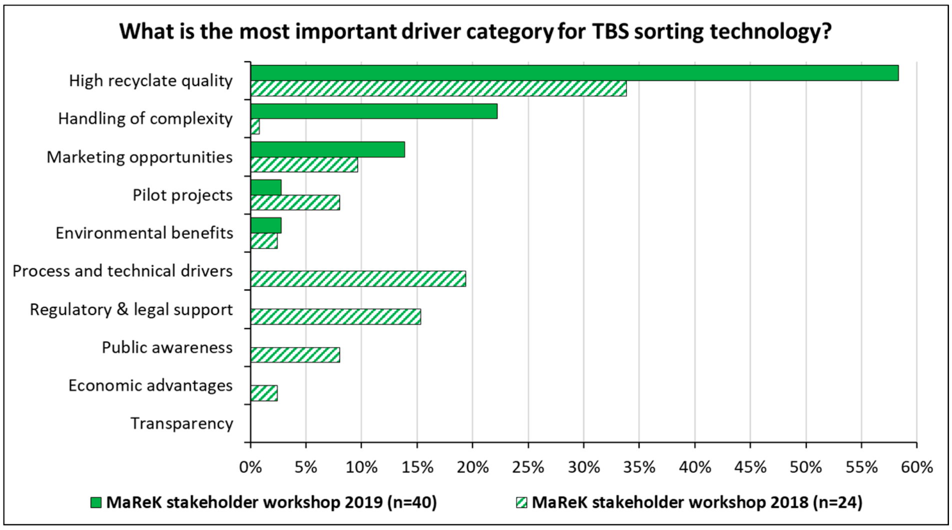

Figure 4. Perceived driver categories for the TBS sorting technology. Own illustration.

The TBS application ideas have been assessed by the participants with respect to feasibility and expected market attractiveness (see Figure 6). The workshop participants saw the highest potential for the application of TBS in the separation of food and non-food packaging (highest attractiveness and feasibility). In addition, the idea of a manufacturer- or brand-specific TBS separation seems attractive (especially from the point of view of the producers), but difficult to realize in practice. The feasibility of the TBS application ideas was rated better by the participating recyclers than by producers and packaging manufacturers. The attractiveness of the TBS application ideas, however, was rated less positively by the recyclers than by other stakeholder groups.

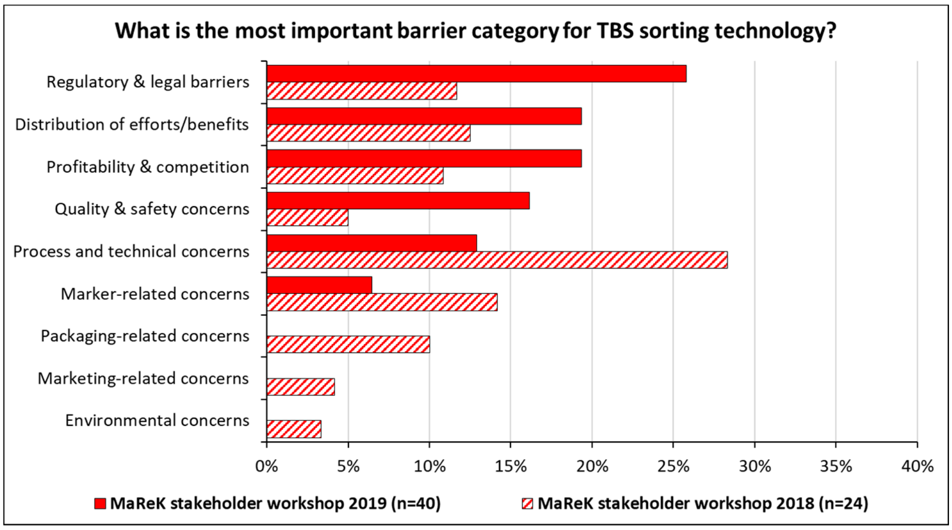

Figure 5. Perceived barrier categories for the TBS sorting technology. Own illustration.

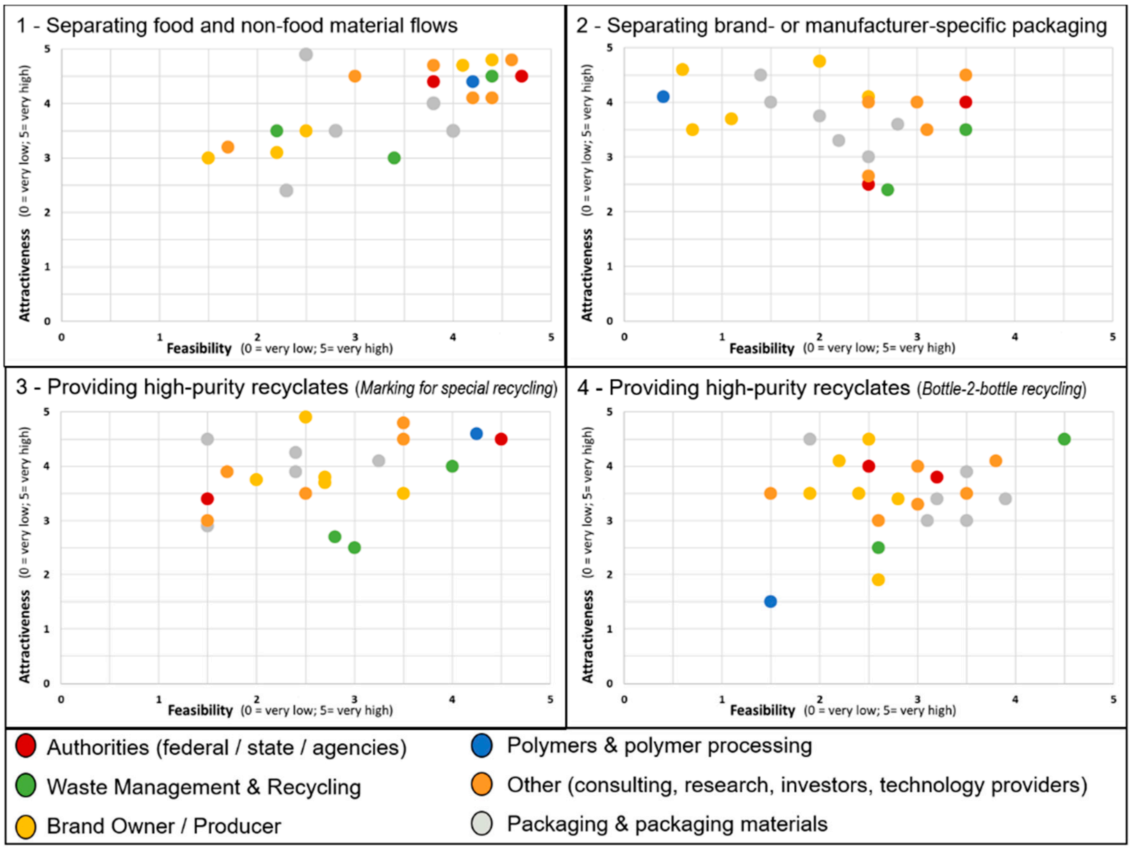

Figure 6. Workshop participants' assessment of feasibility and attractiveness of TBS application ideas developed within the workshop. Own illustration.

3.2. Results of External Environment Analysis (EEA)

To achieve more progress with respect to resource efficiency, a successful collaboration and interplay of political factors are crucial. Experts see the need for "congruent strategies and targets, coherent institutional arrangements and policy systems and distinct and consistent incentive systems and relevant side policies which are credible and aspirational for actors and stakeholders" [38]. To foster the transition to a circular economy, proactive governments and business organizations are increasingly analyzing strategic policy options and their potential impacts [39,40].

Due to strong regulation and incentives to promote the transition to a circular economy, Europe is regarded as a pioneer in the plastics recycling industry [41]. This is reflected in high recycling rates and ambitious targets formulated by industry associations [42–44]. The European Commission is supporting circular economy approaches in three initiatives: the circular economy package (2015), the European innovation partnership on raw materials (2012), and the EU's Horizon 2020 research and innovation program [39].

Furthermore, the EU Strategy on 'Plastics in the Circular Economy' is an overarching plan to support the transition towards a circular economy for plastic materials in the EU and another important means to reduce marine littering [45]. The common understanding of how plastics are produced, used and reprocessed has to be rethought in a visionary way, to improve the design of plastic products and to increase their reuse and recycling, amongst other solutions. Objectives of this EU strategy are [46]:

- Improvement of collection, sorting and recycling infrastructures
- Establishing (new) markets for recycled plastics and providing incentives
- Incentives for smart design, e.g., design for recycling
- Strategies to help reduce environmental pollution caused by plastic littering

As of 2018, China has enforced an import ban on packaging waste. Until then, the country has been the largest export market for German plastic waste. Thus, Germany and other European companies now have to recycle more packaging waste on their own territory [47].

Certain countries (e.g., China) have had a successful and differentiated raw materials strategy for quite some time. In Germany, a raw materials strategy update was published in 2020. For such a country like Germany poor in raw materials, recycling is of existential importance, as it reduces import dependencies [48].

With regard to economic developments, waste prevention and recycling will be the focal point of new production approaches and new business models. Great economic potential is seen in the principle of the circular economy, especially for the current food and packaging industry [48,49].

In order to foster a circular economy, innovative packaging solutions should be implemented with a holistic perspective from the very beginning. Manufacturers and retailers should pursue sustainability in packaging within a collective strategic approach, e.g., a common circular economy concept, instead of individual actionist measures [47].

Global annual exports and imports of plastic waste have been growing rapidly in the last decades. High income countries have overwhelmingly been the primary exporters of plastic waste since 1988, contributing to 87% of all exports and valued at 71 billion USD. Since recording this data, China has imported the vast majority of plastic waste (at least until implementing the import ban in 2018) [40].

Costs of recycled plastics compete with the costs of virgin plastics. Investments to improve mechanical and chemical recycling technologies are necessary to ensure high quality of the recyclates and to be economically competitive with virgin materials. High purity recyclates have a higher economic value and the potential to open up new markets [41,44].

Current raw material prices do not reflect the future scarcity of raw materials and the environmental impact of extraction, so there are no further important economic incentives to conserve primary resources [48].

A significant change in the economic framework for plastics recycling was decided by the European Council in July 2020: The so-called plastics tax is to come into force as early as January 2021. In this context, each EU member state has to pay a levy (0.80 €/kg) for non-recycled plastic waste into the EU budget. Representatives from industry and industry associations warn that this measure is rather detrimental to developments in the field of waste management and recycling [50], while representatives of environmental NGOs are calling for tougher targets [51].

A view from the socio-cultural perspective shows that producers, retailers and customers of consumer goods are willing to decrease the amount of plastic waste and to pursue sustainable products and concepts. However, the amount of plastic waste is still increasing due to social and demographic changes: The world population is growing, online retailing is on the rise, more people are living in small (one- or two-person) households, the number of elderly people is increasing in western societies [40,41,47].

Consumer acceptance of innovative packaging approaches is high—as is the expectation on manufacturers and retailers to make their packaging more sustainable [47]. At the same time, scientific studies and media, see the need of raising awareness among consumers. Handling of plastic waste (avoid littering, explain waste separation) as well as adequate information about sustainable substitutes and purchasing options have to be improved [44,45]. On the other hand, the environmental pollution caused by plastics disposed of is increasingly being covered by the media and is being discussed more and more frequently by the public. Sustainable disposal and recycling of plastics are therefore becoming increasingly important to the (German) population [52].

Many food and packaging specialists and end consumers show a lack of awareness of new available technologies or are general skeptical towards new technologies. As a consequence, new packaging solutions and their potential to reduce environmental impact can rarely be explored on a large-scale market [49].

Further, some technological developments are worth mentioning. High-purity material recovery is of increasing importance to maintain quality of materials and to avoid downcycling. For many materials, 100% recycling (or 100% closing the loop) of packaging waste is neither technically possible nor economically viable. [47,48].

For the purpose of high-purity material recovery (and higher recycling rates), reliable separation and collection by type is an absolute prerequisite for most recyclable materials. Contaminants and harmful substances have to be excluded from materials cycles [44,48]. Chemical recycling which is currently under discussion is said to provide a complementary part to mechanical recycling [44].

In the last decade, Europe has been investing into new packaging technologies. However, only a few of them made it from successful lab-scale application to successful implementation on the market. The main barrier is insufficient collaboration and communication between stakeholders throughout the value chain [49].

According to stakeholder interviews in the study of Locock et al. [41], each polymer group has its specific technological recycling challenges, which include, e.g., quality of waste streams, compound and multilayer packaging, separation of PET and thermoplastic textiles, and opacity of recyclates.

Marking of polymers and polymer packaging from a technological perspective is not necessarily limited to fluorescent tracer application as followed in the TBS approach. If specific surface properties such as embossed surfaces or printing elements either on the packaging material or on labels are applied, this opens options for identification of packaging properties independently from the mere material properties. The idea is to apply e. g. invisible structures which serve the same purpose like (visible) QR codes for identification. Parallel to the development of TBS, technology approaches to improve sorting and recycling of plastics packaging are being followed (see e.g., project Holygrail [53] and Digimarc [54]). The feasibility of these optical identification processes using fine surface or printing structures under real waste management conditions is currently a matter of research.

Considering environmental aspects, a huge share of global plastic waste is being landfilled or ending up in marine and terrestrial ecosystems [41,45]. In addition to the increasing quantity of plastic litter, the long life of plastics is problematic, as are the effects of the growing microplastics generation and toxic additives in plastics. All this leads to adverse effects on the environment and humans [41].

Investments in the technical and organizational optimization of the environmental services sector lead to reduction or avoidance of greenhouse gas emissions: In terms of climate protection, secondary raw material is often superior to primary raw material (less energy for production, shorter transport routes) [48].

Industry-related sources propose a credible and effectively sustainable packaging strategy based on ecological effects and consumer requirements. It is important to take a comprehensive and holistic approach for all types of packaging [47,49].

Certain legal trends are observable, i.e., the European Commission is committed to reduce the effects of marine littering and to increase the value of material streams in the EU economy (EU Action Plan for the Circular Economy [5]). In the final adoption of the EU Circular Economy Package waste-related directives include:

- A common EU target to recycle 70% of packaging waste by 2030; including additional recycling targets for specific packaging materials (e.g., plastics 55%)
- Economic incentives for producers to offer greener products and support recovery and recycling schemes: Minimum requirements are established for extended producer responsibility schemes to improve their governance and cost efficiency [45].

The basis for regulatory measures is primarily an improved recyclability of the packaging itself ("Design for Recycling"). The waste policy objective of introducing quotas is primarily the gradual qualification and diversification of the recycling industry. However, this goal can only be realistically achieved if future regulations ensure (i) an equally growing sales market for the increasing quantity of reusable materials and recyclates, and (ii) the quality of valuable materials and recyclates will take precedence over pure quantity [48].

The EU legal framework for recycling targets and reuse of plastics in the packaging sector is a frontrunner in terms of regulating plastic recycling. However, in some reports it is also considered to be slow and overly conservative [41].

3.3. Results of Business Model Development (BMD) Activities

In an extensive analysis, suitable business models were developed. Due to the ongoing commercialization of TBS, they cannot be presented in full detail here. The following main characteristics describe the most promising aspects that were obtained [55].

- Focus on brand owner/distributor: The benefit of using TBS is the possible production of high-quality and attractive products and packaging, provided that the legal requirements are observed. It is important here that the use of recycled material is also recognizable to the customer of the brand owner and that the price of recycled material is lower than that of primary raw materials.
- Focus on waste management companies: For waste management companies, the sorting and disposal of increasingly complex plastic packaging is becoming an ever greater challenge. If a waste management company is entitled to market the sorted products itself (and does not only offer sorting services to plastic waste owners) it could achieve higher prices by producing high-quality recycled material. This could be enabled by TBS which could replace existing technology to achieve a better sorting accuracy.

In addition, the business model patterns in Table 2 seem potentially attractive for the TBS technology (according to market feedback from experts which were interviewed). In order to concretize TBS application in the market, the following two scenarios were developed in the project consortium [18]:

- "TBS-complete": TBS replaces the main sorting processes of a common packaging sorting system after the first magnetic separation, and leaves earlier sorting steps unchanged. TBS-complete is intended to achieve sub-fractions of the previous fractions of the plastics PET, PP and PE, or even additional fractions with new specifications at the end of the sorting process and a higher quality of the sorted products in terms of sorting purity.
- "TBS-light": The TBS machines are added to the existing sorting system at the end of the sorting processes for the plastic fractions PET, PP and PE. This means that post-sorting is carried out, for example to sort out multilayer packaging or packaging materials with certain material additives and properties such as oxygen barriers. This

would leave the original sorting process unchanged and the TBS machines would be relatively easy integrated into complex systems.

Table 2. Potential business model patterns for TBS.

Business Model Pattern	Application to TBS
Cross selling	In addition to the tracer, packaging with recycled material is offered.
Fractional ownership	Joint procurement and use of a sorting plant (cooperation between brand owners and waste management companies).
Push to Pull	Focus on customer needs by adding flexibility to own processes.
Leverage Customer Data	Waste management companies collect data on material flows make them available to brand owners.
Pay per use	The effective consumption of the tracer will be charged.
Subscription	A form of subscription to tracers.

Source: [55], adapted from [35].

It is expected that "TBS-complete" will be difficult to implement in Europe and especially Germany, since sorting of packaging there has already a high degree of technical maturity and relies on complex coordination in the value chain. Hence, "TBS-light" seems to be more attractive there, while "TBS-complete" seems to be more attractive for a market outside Europe.

4. Discussion and Conclusions

There is a strong willingness to discuss major changes in the current plastics recycling system. In the research project MaReK, TBS was further developed for use in waste management and its application shown in a demonstration plant for sorting of plastics packaging. The mixed method approach presented in this paper showed that the technical potential of the TBS technology is clearly acknowledged by stakeholders.

There are two promising application scenarios for TBS: "TBS-complete" (TBS replaces the main existing sorting processes) and "TBS-light" (the TBS machines are installed downstream of existing sorting systems, leaving the original sorting process unchanged). The latest technical results have just proven that with "TBS-complete" tracer quantities of 1–10 μg per cm^2 of printing ink or 1–10 ppm in the packaging material (polymer) are sufficient to achieve reliable detection and thus sorting into 20–30 fractions for all packaging. Compared to the costs of the current sorting system, TBS will be at a roughly similar level, but with significantly improved sorting quality and efficiency. This is exactly the development that the recycling market is demanding in order to offer specification-compliant high-purity recyclates at economic prices.

However, we have identified key challenges in the implementation of TBS as a promising technology for the circular economy of plastics. In the following list, we briefly describe these key challenges and discuss the implications on the further technology and market development for TBS (in brackets: method used to derive the aspect shown):

- The technological approach of TBS has to be compatible with existing sorting and recycling processes. (IISA) → Based on practical know-how and recent scientific findings, technical recommendations were made to adapt the existing technology concept for better integration into existing recycling processes. (IISA; EEA)
- Many industrial stakeholders show a low willingness use the new technology since it has not been fully proven in an industrial application (also due to the dominant design of the existing recycling processes). (IISA; EEA) → In a workshop with industry representatives, practical TBS application ideas were specified, tested and evaluated. The highest potential is seen in the application of TBS to separate food and non-food packaging. (IISA)
- The composition of the value chain in packaging recycling implies that different stakeholder groups (in particular brand owners, waste management companies and recyclers) must be involved simultaneously in the implementation of the TBS. (IISA; BMD) → The expected value chain of plastics recycling with TBS was derived as

the basis for addressing possible changes for stakeholders and for developing an appropriate business model. (IISA)

- Necessary efforts and expected benefits can be unequally distributed along the value chain requiring a mechanism for compensation to be established. (IISA; BMD) → The intensive dialogue with stakeholders must be continued not only to analyze but also to demonstrate the feasibility and the benefits of TBS. Furthermore, regulators need to be involved to ensure that recycling rules are adapted to provide incentives for the practical adoption of innovative and sustainable approaches such as TBS. (IISA; EEA)
- It is assumed that the greatest economic and environmental benefits can be gained if TBS comes along with a radical change of the current plastics recycling system, i.e., the replacement of large portions of the current sorting techniques by a single TBS process (scenario "TBS-complete"). (IISA; BMD) → Business cases and business model options have to be specified, a detailed cost structure and customers' willingness to pay for the offering of tracers and TBS detection units have to be determined. (BMD)

On the basis of these findings and practical recommendations, the team of the MaReK research project was able to advance the development for the TBS in a responsible and sustainable way. In an iterative process, important advice for interaction with relevant actors in the plastic packaging value chain was obtained and governance approaches for improved regulation by policy makers were developed.

However, there are also limitations. First, parts of our methodology rely on stakeholder inclusion, which requires a lot of effort and is time-consuming. Consequently, we have not been able to empirically collect a large amount of stakeholder information. Our results should therefore be seen more as preliminary, based on qualitative information of several relevant stakeholders. Second, we have to deal with the dilemma of dominant design in existing recycling processes. Brand owners, recyclers, and legislators are hesitant to make a first step and are each expecting others to assume a leading role. How this dilemma can be overcome should be the subject of further investigation. Third, our research has a strong link to the German and European context. Due to the potential of the TBS technology, however, further countries with less developed waste systems should be investigated with regard to a possible implementation of the technology.

This research can be seen as a practical contribution to the responsible and sustainable implementation of a radical technology-based innovation for the circular economy of plastics. Our approach helps to systematically understand and address the occurring challenges in the innovation process. Practitioners can use the methodological approach from this paper to obtain concrete recommendations on how to focus and improve their R&D and business development activities. These steps are an important prerequisite for developing sustainable business models for technologies that have the potential to enable a true circular economy for plastics.

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