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Expert Survey on the Impact of Cardboard and Paper Recycling Processes, Fiber-Based Composites/Laminates and Regulations, and Their Significance for the Circular Economy and the Sustainability of the German Paper Industry

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Abstract: The European Community is striving for a sustainable society as suggested by the UN's 2015 sustainability goals. The circular economy in the paper and packaging industry is of particular importance here because it consumes many resources. The paper industry in Germany with a fiber recycling rate of 85% in 2022 is already a pioneer and role model for other industries. All materials should be recyclable. Fiber-based composites/laminates are currently becoming increasingly important. Essential questions are: which collection systems and recycling paths should be used for fiber-based composites/laminates, and where are there currently challenges with recycling? To answer these questions, 58 questionnaires answered by German experts and practitioners in the German paper industry were evaluated. Wet-strength papers, adhesives, plastic coatings and wax dispersions were perceived as a problem by 70% of all respondents, and packaging residues by almost 40%. Additionally, 90% stated that the composition of paper for recycling changes regularly due to legislation, trends and innovations, while 60% attributed this to recent changes in legislation. For at least 80%, virgin fibers from packaging are valuable for paper recycling, but only 15% of respondents stated that virgin fibers compensate for the disadvantages of rejects. Almost 90% expected challenges with fiber-based composites/laminates in the existing paper for recycling processes. Overall, the collection and recycling of fiber-based composites/laminates in conventional paper for recycling collection and the recycling system is not desirable. An integrated collection, sorting and recycling system should be considered, especially because a further increase in fiber-based composites is to be expected. In the end, the design for recycling and following recycling guidelines are the key to the recycling industry in the future. Good recyclability of fiber-based composites/laminates would improve their acceptance by paper recyclers. Their virgin fibers are particularly valuable. The results of our study are relevant to the recycling and fiber industry, standard-setting bodies, regulatory authorities and research. The limitation of this study is that experts from the paper industry were interviewed, but the recyclability of the fiber materials was not analyzed by measurement, and the machine technology of the interviewees could not be examined and evaluated.

Keywords: circular economy; design for recycling; packaging legislation; paper recycling; impact of policies and laws relating to sustainability; renewable materials; renewable sourcing; sustainable economy; sustainable utilization of resources; virgin fiber

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1. Introduction

Recycling packaging is becoming increasingly important. In Europe, the circular economy is being promoted with the "Green Deal" [1–3]. The resulting legislation and organization are extensive and complex, and the design of the legislation is the subject of current political decisions. Western European countries such as Germany are currently leading in the circular economy [3], especially with fiber-based materials such as newsprint, magazine, paper cardboard and corrugated board. This makes the paper industry a pioneer and role model for other industries. Many companies have set themselves targets for the application and use of circular packaging [4]. Mandatory recycling quotas are set in various directives. In the case of fiber-based materials, however, increasingly used composite/laminate packaging poses a challenge for recycling. In order to better understand how the recycling of these materials can be improved in practice and what impact the legislation has on this, it makes sense to obtain expert assessments from the paper and recycling industry. Therefore, the aim of the work was to determine whether the recycling of fiber-based composite/laminate packaging currently leads to and will lead to challenges in paper recycling in the paper industry and whether this has an impact on the paper quality produced. In addition, it was to be determined whether current legislation and new developments in fiber-based composite/laminate packaging have an influence on this.

2. Literature Review

2.1. Environmental Impact of Paper

The basis for paper and fiber-based packaging are cellulose fibers. These are a renewable raw material that bind CO_2 during growing. Nonetheless, the production and use of paper has an environmental impact, with details in life-cycle assessment reports [5–9]. A distinction must be made between the extraction of the fibers and pulp and the production of paper from them. Fiber extraction is resource- and energy-intensive [7].

After paper- and fiber-based packaging has been used, it can be landfilled, incinerated, used for bioethanol production and/or recycled [10–12]. When landfilled under aerobic conditions or composted, cellulose fibers are broken down into CO_2 and water. Landfilling under anaerobic conditions produces CO_2 and the potent greenhouse gas methane [13]. This type of disposal should, therefore, be avoided, except the methane can be used as biogas [10]. Energy can be recovered during incineration, which reduces the environmental impact. Some LCA studies with system boundaries not including resource use for fiber/pulp production can have better results for incineration and/or bioethanol production [11]. The proportion of recycling of paper and fiber-based packaging is by far the largest at 85% in 2022 in Germany [14].

However, the advantage of recycling is that already-extracted fibers can be used, the resource requirement for virgin fibers is avoided, and less wood is needed for new fibers [7,8]. This also results in a cost advantage. Between 2010 and 2020, for example, paper for recycling "Old Corrugated" cost 70–220 USD/Ton (export price), and "High Grade De-inked" cost 130–360 USD/Ton [15]. Fresh fiber pulp is significantly more expensive, at 650–950 USD/Ton for "Deinked Pulp" and 850–1450 USD/Ton for "Northern Bleached Softwood Kraft" between 2010 and 2020 [15].

In a study for the German Environment Agency, it is written that "It can be concluded though, that an increase of use cycles of fibres not only reduces the amount of virgin fibres needed, but will also lead to overall benefits in the environmental performance of office paper products. It should therefore be aimed to increase the use of recycled fibres" [9]. Fibers age and change their properties by recycling [16]. However, "After up to 25 recycling cycles on a laboratory scale and 16 cycles on a pilot scale, the fiber material is still suitable for producing recycled paper of almost the same quality" (direct translation from German [17]) [18]. Twenty-five recycling cycles were confirmed by another research group [19]. However, the mean total number of fiber uses might be lower due to losses during recycling [20]. In Germany and many other parts of the world, recycling is, therefore, preferred to incineration with energy recovery, bioethanol production and landfilling. Incinerated with energy recovery is only the reject of the recycling process.

2.2. Paper Recycling in Germany

There are various collection systems for paper for recycling in Germany. Paper for recycling can be collected as commercial/industrial material. This is usually particularly pure. Collection at the consumer level is divided into collection as paper for recycling in certain containers and the sorting of fiber-based packaging from the collection of recyclable materials for consumer packaging. "The dual systems must ensure separate collection for packaging made of paper, cardboard and carton (PPK), while non-packaging made of PPK is the responsibility of the public waste management authorities fall under the responsibility of the public waste management authorities" (direct translation from German) [21]. Paper for recycling from the consumer collection is cleaner and less contaminated than fiber-based packaging from the collection of recyclable materials for consumer packaging. The appropriate disposal routes for fiber-based packaging are currently under discussion. The recycling paths are depicted in the Supplementary File—S1, S2, and S3.

After collection, paper for recycling can be sorted in the first step before repulping. Sorting can be done by dry-sorting [22,23]. Alternatively, paper for recycling from waste collection is directly processed. Before paper for recycling is processed into new paper, it needs to be fragmented, and fibers are dispersed by (re-)pulping [22–24], in which fibers are separated in water from each other. The next step can be a coarse cleaning and screening. Ink, adhesives and other kinds of coatings can be screened out by fine screening. Fragmented, undesired smaller particles, such as stickies are dispersed below the visibility limit and rendered harmless [25]. Some of the impurities that are not removed are processed at the paper machine, and some of these impurities will be found in the paper. The impurities that can be separated are removed and disposed of as rejects. Rejects are incinerated, landfilled or recycled [26,27].

Printing inks are removed from the pulp by deinking, which combines pulping and flotation with additives such as surfactants [22,23,28,29]. By deinking, white paper is produced from paper for recycling [22]. Bleaching is a possible further step to increase whiteness.

During recycling of paper, the fiber quality and some mechanical properties of the paper made of these recycled fibers reduce [16–18,30,31]. A deterioration process is hornification [16,30–35].

Various test methods have been developed to assess the recyclability of paper, cardboard, paperboard and fiber-based composites [36].

For 2012, it was reported that globally, more than 50% of paper was recycled, and the rest was mostly incinerated, incinerated with energy recovery and landfilled [37,38]. In 2023, the recovered paper utilization rate in Germany was much higher, at 83%, and the recycling rate was 85% [14]. This makes the German paper industry a role model when it comes to recycling. The proportion of packaging paper for recycling will increase because in OECD countries such as Germany, the consumption of newsprint and printing paper is falling sharply, but the consumption of packaging paper is falling only slightly, stagnating or even increasing slightly until 2050 [39].

2.3. Paper Laminates, Coated Paper and Treated Paper

Paper has an insufficient water resistance; untreated paper has a high permeability for gas vapors and liquids, and paper is not a thermoplastic, and, therefore, it cannot be sealed. To increase the wet-resistance, wet-strength additives are used in bulk [40–43]. For gaining oxygen, water vapor, and fat barrier, paper is wet-coated with dispersions and solutions of wax, proteins, polysaccharides, polyethylene, polyvinyl alcohol, starch-based coatings and others [44–53]. Such coatings are applied to a thickness of a few micrometers; therefore, such coatings are prone to disperse during repulping. By extrusion coating, polymer layers are applied from the melt, such as PE-LD, PE-HD, PP, PLA, PHBV, PET and others [54–60]. Layers applied by extrusion coating are mostly thicker than layers applied by wet coating and mechanically more stable; therefore, such layers are less prone to disperse during repulping. Extrusion-coated layers can, therefore, be more easily removed and rejected during pulping.

2.4. Legislation in Europe and Germany and Significance for Paper Recycling

An important law in Germany is the "Act on the Placing on the Market, Return and high-quality recycling of packaging (Packaging Act-VerpackG)" (translation from German) from 2017 (date of issue, last modified on 25 October 2023) [21,61]. It not only regulates the placing of packaging on the market but also the take-back and high-quality recycling of packaging waste. Strengthening the recycling of packaging waste collected by the dual systems was an important regulatory content and an innovation of the Packaging Act, in particular by increasing recycling rates and taking ecological factors into account when determining system participation fees. The Packaging Act strengthens the system by establishing a central control and monitoring mechanism, the Central Agency Packaging Register (German "Zentrale Stelle Verpackungsregister", ZSVR). In addition, a legal basis for the (voluntary) uniform collection of recyclable materials has been established. The Packaging Act also promotes reusable packaging by introducing and gradually extending the mandatory deposit for single-use drinks packaging and introducing a mandatory information requirement in the retail sector. Manufacturers of packaging filled with goods have two important obligations: From 1 July 2022, they must register in the LUCID packaging register before placing this packaging on the market (Section 9 VerpackG). They must also ensure that packaging is taken back by one or more dual systems across the board before it is placed on the market. The task of the Central Agency Packaging Register (ZSVR) is to ensure that competition between market participants is open and fair. Every year, the Federal Environment Agency collects information on packaging waste, analyzes it and reports to the European Commission in accordance with its reporting obligations. In the Packaging Act, the legislator has assigned a number of sovereign tasks to the Central Agency Packaging Register Foundation (ZSVR). It monitors the LUCID Packaging Register and determines, for example, which packaging is subject to system participation. However, the responsibility of the state is not completely transferred. In accordance with Section 29 (1) of the Packaging Act, the Federal Environment Agency monitors the ZSVR to ensure that the tasks are properly fulfilled.

According to §3 (8) of the Packaging Act, "Packaging subject to system participation is sales packaging and secondary packaging filled with goods which, after use, typically generated as waste by private end consumers after use" (translation from German).

All producers subject to the Packaging Act are obliged to report the quantity and material of the packaging they place on the market to the Central Agency Packaging Register. The data must also indicate which dual system the producer participates in (Section 10 (1) VerpackG). As the law does not stipulate a threshold value for the size of the company required to register, small producers or retailers must also register.

In accordance with Section 16, the systems must annually forward at least the proportions of packaging supplied to them for preparation for reuse or recycling as shown in Table 1. This table provides an overview of the targeted quotas under German legislation from certain points in time (Section 16 (2) VerpackG).

Table 1. Targeted recycling rates for fiber-based packaging in comparison to plastic packaging in Germany according to VerpackG [21,61].

Material	from 2019	from 2022
paper, board	85%	90%
beverage carton packaging	75%	80%
plastic	58.5%	63%

According to the Packaging Act §3 (5), composite packaging is defined as follows: composite packaging is "packaging that consists of two or more different types of material, which cannot be separated by hand" (translation from German) [61].

According to §16, (3), "In the case of composite packaging [. . .]", "[. . .] in particular, the recycling of the main material component must be ensured, unless the recycling of another material component better meets the objectives of the circular economy" (translation from German) [61].

Pursuant to Section 21 (1), "systems are obliged to create incentives in the assessment of participation fees in order to:

1. Promote the use of materials and material combinations in the production of packaging subject to system participation that can be recycled to the highest possible percentage, taking into account the practice of sorting and recovery.
2. Promote the use of recyclates and renewable raw materials".

According to §21 (3), "The Central Agency shall, in agreement with the Federal Environment Agency, publish a minimum standard for the assessment of the recyclability of packaging subject to system participation, taking into account the individual recycling routes and the respective type of material, by September 1 of each year" (translation from German) [61].

To be considered recyclable, packaging must be recyclable in itself, and a recycling infrastructure must be established and made available. According to the minimum standard, many fiber-based packaging materials are recyclable, as shown in Table 2 [62]. That means in total, most of the fibers are already recycled. However, in the case of fiber-based composites/laminates, the recyclability is existing, but to a limited extent, possibly due to the recycling infrastructure that has to be developed for such materials. In the minimum standard, incompatibilities for paper/paperboard/cardboard, fiber-based composite packaging and liquid packaging board are stated as "water-insoluble or non-redispersible adhesive applications and polymeric thermoplastic dispersion coatings, unless it is proven that they do not lead to incompatibilities in the recyclate. The exceptions granted for hotmelt adhesives in the ERPC Scorecard apply (softening temperature of the adhesive (according to R&B): $\geq$68 °C, layer thickness (non-reactive adhesives): $\geq$120 µm, layer thickness (reactive adhesives): $\geq$60 µm, horizontal dimension of the adhesive application (in either direction): $\geq$1.6 mm)" (translation from German) [62].

Table 2. Recycling classification for fiber-based packaging in Germany according to minimum standard; PPC means paper/paperboard/cardboard [62].

Packaging Types	Main Component Material	Recycling Infrastructure Existence per Group Number
Liquid packaging board	Paper, paperboard, cardboard	Given, 512/510
PPC packaging (excluding fiber-based composite/laminate packaging), corrugated board, folding boxes, paper bags and pouches, etc.	Paper, paperboard, cardboard	Given, 1.01.00
Other fiber-based composite packaging (main component not metal), such as laminated folding boxes, composite cans, coated paper, paper cups coated on both sides	Paper, paperboard, cardboard	To a limited extent, 550

3. Materials and Methods

An expert survey was chosen as the method for gaining knowledge because experts have aggregated experience. The survey was conducted with the survey tool LimeSurvey (LimeSurvey GmbH, Hamburg, Germany). The survey was conducted using verbal rating scales. In the survey, attention was paid to the quality criteria of empirical research—objectivity, reliability and validity—in order to be able to derive representative results [63]. The original survey is in the Supplementary File, S4.

The following company categories were contacted for the survey: all German paper mills that manufacture products from paper for recycling. Contact data were taken from the Paper Recycling Business Directory ENF LTD (Coventry, UK; https://www.enfpaper.com/, accessed on 31 July 2023), the Internet database Birkner-International PaperWorld (Birkner

GmbH & Co. KG, Hamburg, Germany; https://www.paper-world.com/, accessed on 31 July 2023), and the contacts for the paper industry of the author Jürgen Belle from Munich University of Applied Sciences.

A total of 73 companies and 136 contact persons at these companies were collected and contacted. (Germany has 89 companies in the pulp and paper industry, with 142 mills; figures for 2023 [14]). The number of companies was reduced to 63 based on feedback, such as responses that companies do not manufacture products from recovered paper, companies have merged with others or there have been business closures or absences due to illness that make it impossible to answer the questionnaire. After deducting the emails returned as undeliverable from the 136 contact persons, 110 contact persons remained. The survey was completed in 58 cases, meaning that approximately half of the respondents completed the survey. The survey was conducted from December 2022 to March 2023.

Representativeness is attempted to be achieved through random sampling [64]. Random does not mean arbitrary, but that each statistical unit has the same probability of being included in the sample [65]. A truly random sample is difficult to realize. However, it is assumed that a simple random sample was used for the analyses presented in the following chapters, at least in theory, and that the practical implementation comes very close to the claim associated with this, in that each of the 110 survey participants had an equal chance of being analyzed.

4. Results and Discussion

4.1. Classification of Surveyed Companies

Most of the companies interviewed were large companies (Figure 1).

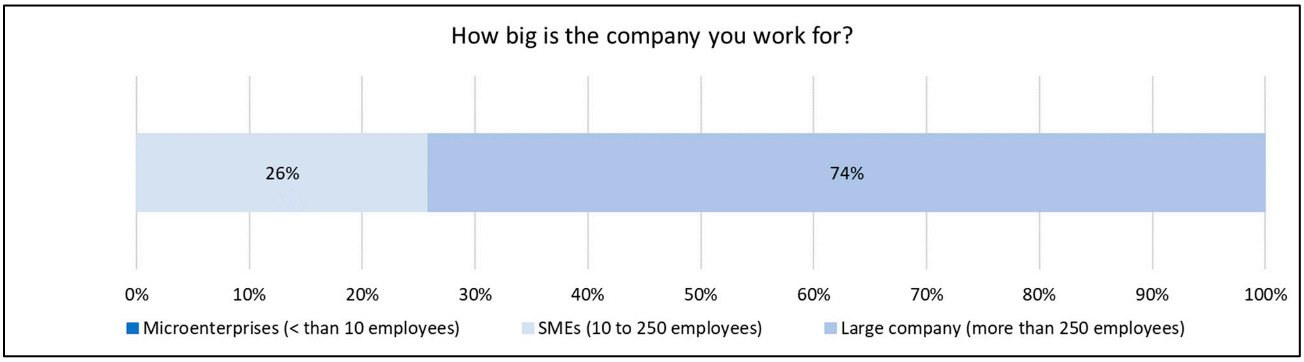

Figure 1. Size of company (all companies $n = 58$, large companies $n = 43$, SME $n = 15$, microenterprises = 0; SME: small and medium-sized enterprise).

With the exception of graphic papers, small and medium-sized enterprises (SMEs) and large companies produce various types of paper (Figure 2). The SMEs dominated in paper and cardboard for technical purposes and corrugated board papers. The results harmonize with production volumes in 2023 in Germany, with a domination of packaging paper [14]. The share of main grades of total production is 62.9% paper and board for packaging, 22.2% graphic papers, 7.5% other paper and board, and 7.4% sanitary and household; all grades together have an annual production volume of 18,646,595 t [14].

Most of the interviewed companies do recycling for packaging paper, including corrugated board (Figure 3). Deinking is dominated by large companies. Deinking is important for graphic paper production to produce white paper [22], which is also dominated by large companies (Figure 2), and, as expected, producers of graphic paper (Figure 4), for which results are consistent and plausible.

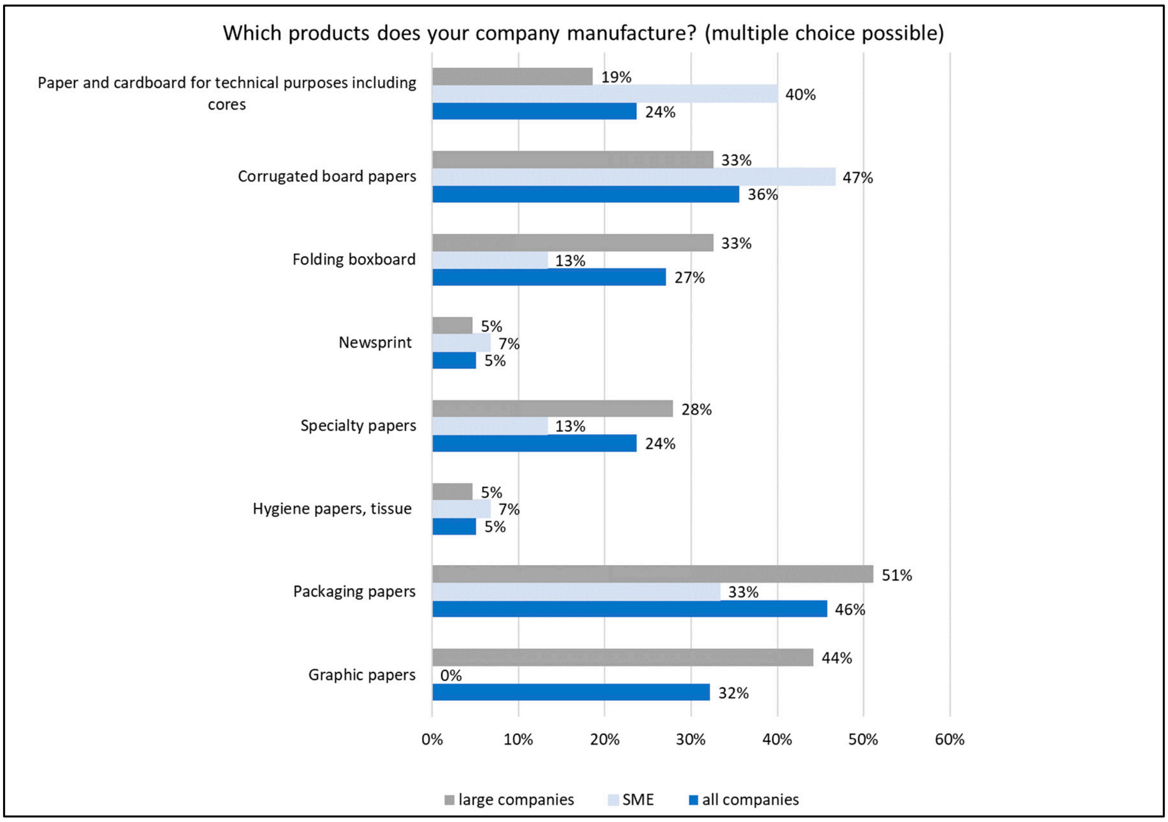

Figure 2. Products of the companies (all companies n = 58, large companies n = 43, SME n = 15; SME: small and medium-sized enterprise).

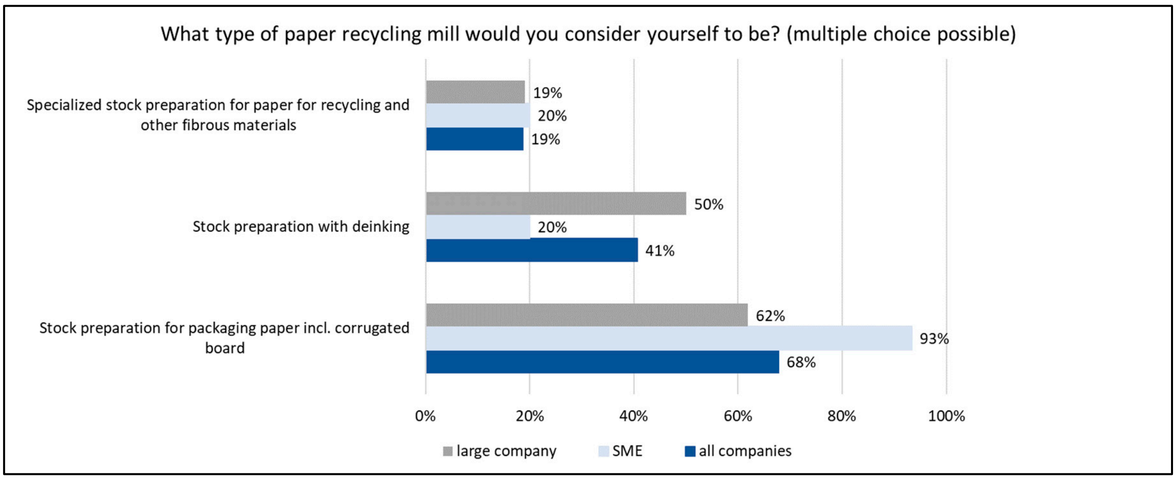

Figure 3. Type of paper recycling mill in relation to the size of the paper mill (all companies n = 58, large companies n = 43, SME n = 15; SME: small and medium-sized enterprise).

Packaging paper recycling dominates for the intention to produce new packaging paper (Figure 4). Deinking to produce fibers for white paper layer is mostly seen for the production of graphical paper, as mentioned before, but also for corrugated board like white top liner for corrugated board. Interestingly, some packaging paper layers are recovered for graphic paper.

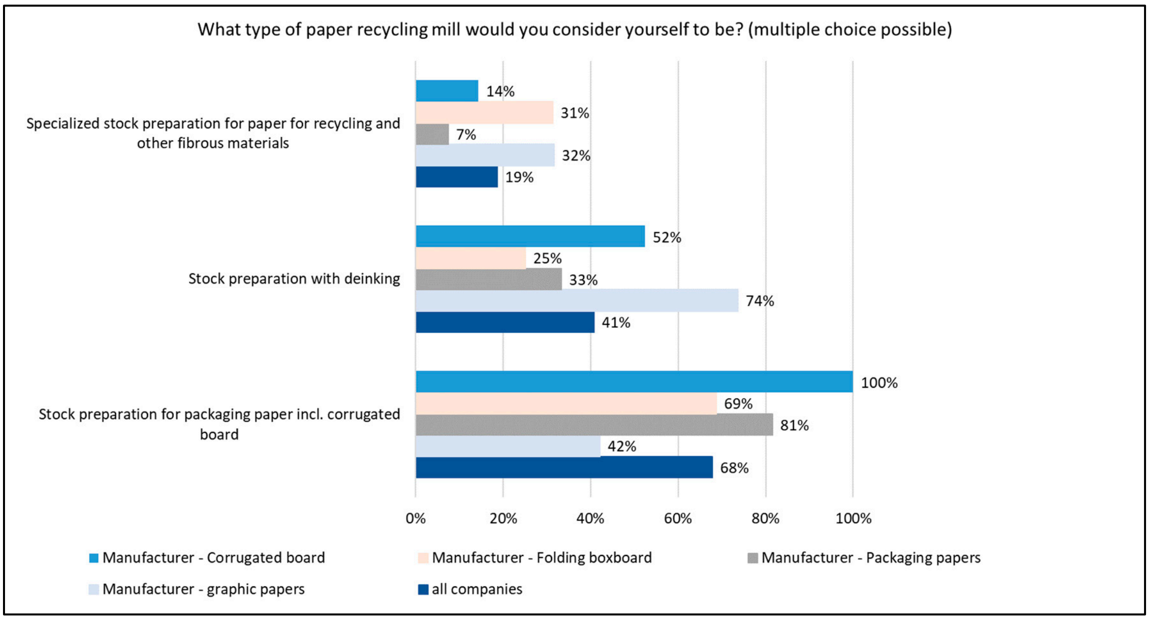

Figure 4. Type of paper recycling mill in relation to the paper produced (manufacturer-corrugated board n = 21, manufacturer-folding boxboard n = 16, manufacturer-packaging papers n = 27, manufacturer-graphic papers n = 19, all companies n = 57).

4.2. Recycling Procedures and Challenges during Recycling

Pre-sorting is relevant for the recycling of paper. Especially, paper for deinking should be separated [22]. Only around a quarter of respondents stated that paper for recycling is provided pre-sorted (Figure 5). Less than 40% of paper for recycling recyclers sort the paper for recycling (Figure 6), and 60% of the paper is never sorted at the recycling companies. Approximately 20% of the paper is never sorted at all (Figure 7). It can, therefore, be concluded that changes in paper quality and composition cannot be compensated for by pre-sorting for up to around 20% of recyclers' use. Problems with these recyclers during the recycling of paper are, therefore, obvious. The rest have at least some measures for sorting available.

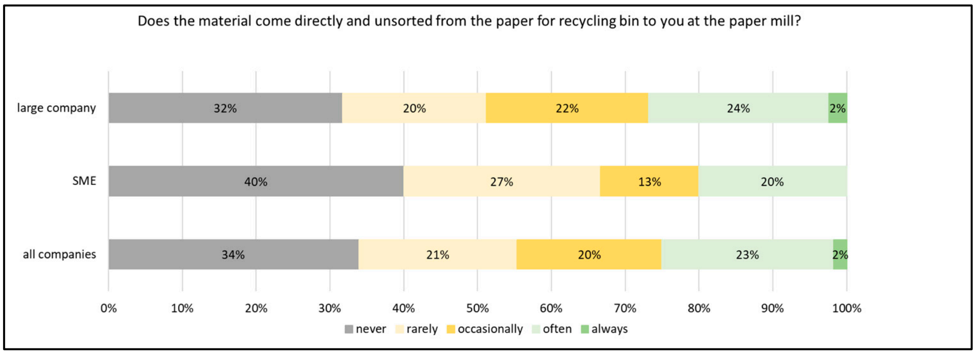

Figure 5. Origin of paper for recycling (all companies n = 55, large companies n = 40, SME n = 15; SME: small and medium-sized enterprise).

From the results presented above (Figures 5 and 6), it can be stated that the current sorting is not used in some case due to several reasons. This is confirmed by the results of the survey that only one-third of the companies processing paper for recycling stated that the collection and sorting systems "often" work (Figure 8).

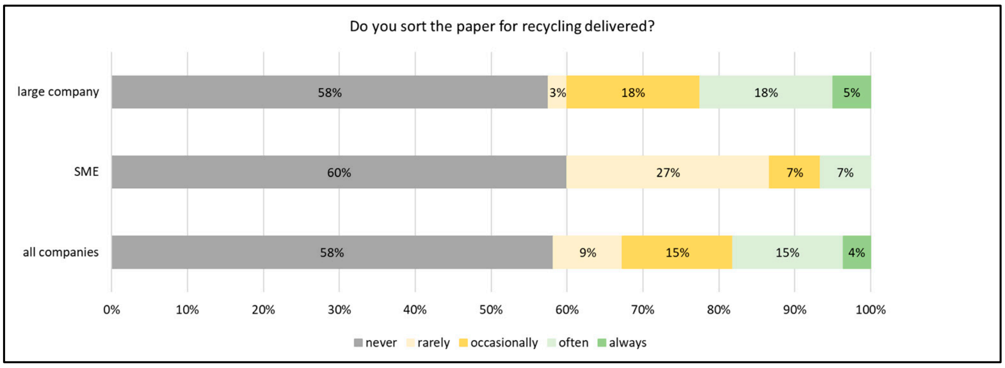

Figure 6. Sorting paper for recycling at paper company (all companies $n = 55$, large companies $n = 40$, SME $n = 15$; SME: small and medium-sized enterprise).

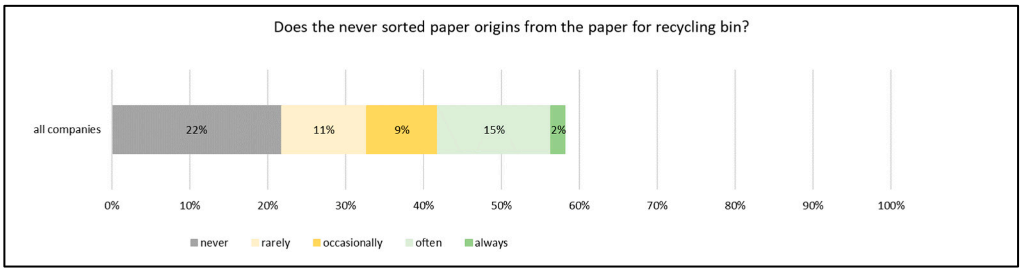

Figure 7. Origin of "never"-sorted paper for recycling ("never" sorted in paper company $n = 32$, derived from Figure 6).

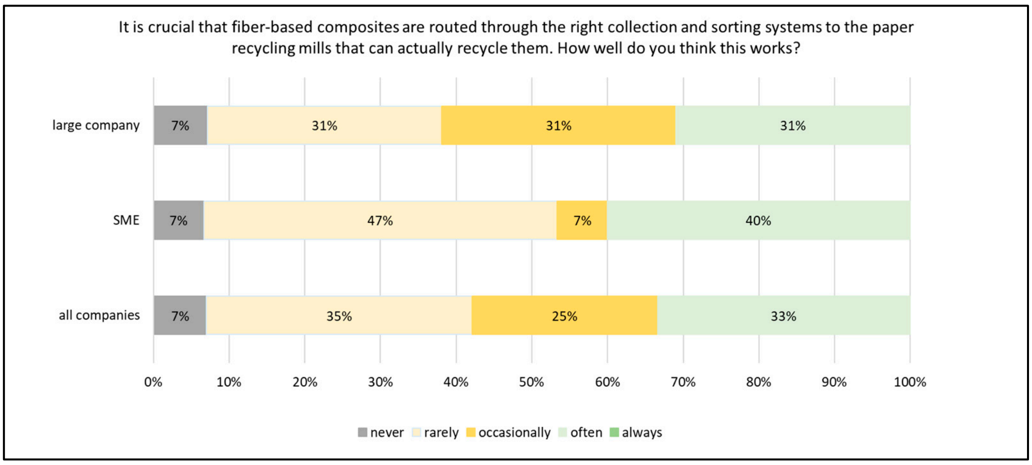

Figure 8. Functionality of collection and sorting systems (all companies $n = 57$, large companies $n = 42$, SME $n = 15$; SME: small and medium-sized enterprise; "always" was not chosen.).

Approximately one-third of the manufacturers of fiber-based composites "always" and "often" reported processing problems (Figures 9 and 10). The companies that "always" reported problems "never" sort the paper before recycling, except in one case "occasionally". It, therefore, stands to reason that paper sorting leads to fewer processing problems. Problems occur more frequently in SMEs. The obvious causes here are a lack of or inadequate investment and procedures for sorting.

Rejects that need to be sorted out and disposed of are an important issue in the paper recycling process. Fiber-based compounds/laminates lead to more rejects for 60% of the companies surveyed and for 80% of SMEs (Figure 11). Half to three-quarters of the companies "always" and "often" have an increased quantity of rejects due to paper recycling independent of their products (Figure 12). Overall, this is detrimental to recycling.

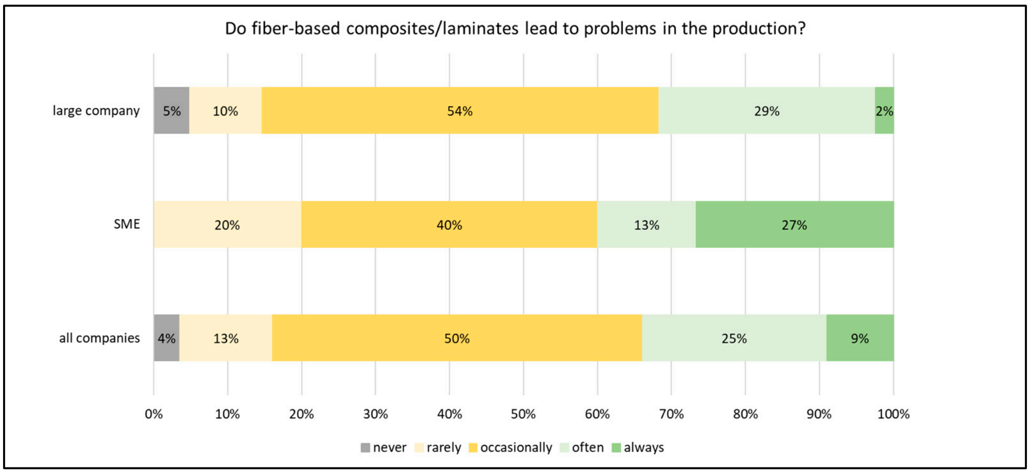

Figure 9. Problems with fiber-based composites/laminates in relation to the size of the paper mill (all companies n = 56, large companies n = 41, SME n = 15; SME: small and medium-sized enterprise).

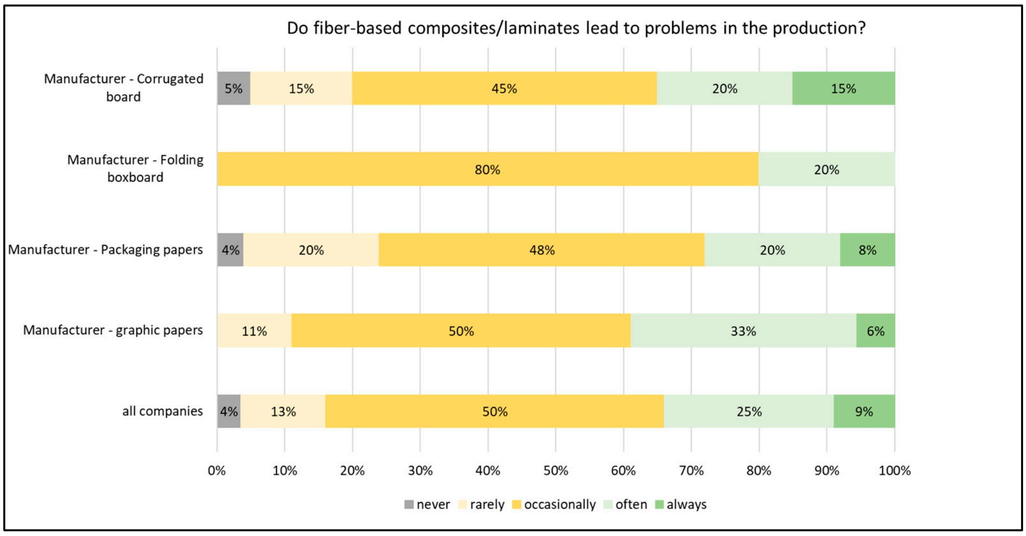

Figure 10. Problems with fiber-based composites/laminates in relation to the produced paper (manufacturer-corrugated board n = 20, manufacturer-folding boxboard n = 15, manufacturer-packaging papers n = 25, manufacturer-graphic papers n = 18, all companies n = 56; one company can produce several products).

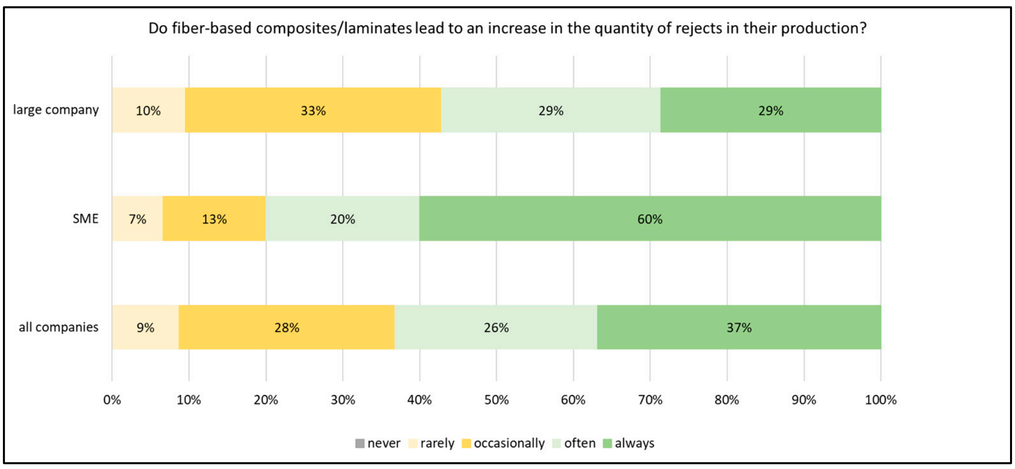

Figure 11. Occurrence of rejects in relation to the size of the paper mill (all companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise; "never" was not chosen).

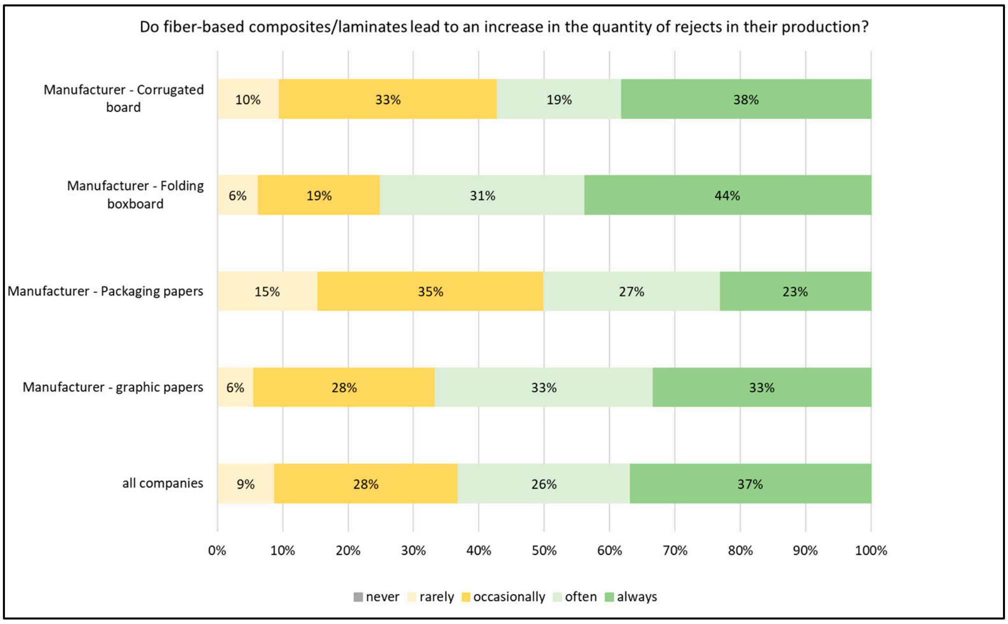

Figure 12. Occurrence of rejects in relation to the produced paper (manufacturer-corrugated board n = 21, manufacturer-folding boxboard n = 16, manufacturer-packaging papers n = 26, manufacturer-graphic papers n = 18, all companies n = 57; one company can produce several products; "never" was not chosen).

For an "Italian recycling paper mill that produces packaging paper using only paper and cardboard from separate collection of municipal solid waste as raw materials", "the amount of pulper rejects generated is about 7% of the raw material in input" [26]. Another publication "estimated reject quantities in the range of 4–10% of recovered paper used in recycled paper production" [26,66]. Deinking will cause higher losses, and more rejects with a lower "yield of recycled pulping (73–89%)", and a reject amount of 11–27% [38]. However, it is not clear from this reference whether deinking is included. However, it is reported that losses during the deinking process are up to 20% and up to 50% when pulp is deinked for tissue paper [22]. For tissue paper ink, inorganic fillers and other particles must be removed.

The packaging industry usually uses virgin fibers for composite/laminate packaging for reasons of approval as a food contact material. An example of a laminate is paper cups extrusion-coated with PE-LD or PLA [55]. Virgin fibers have a higher quality and yield better mechanical properties than already more-than-once-recycled fibers [30,31]. Fiber recycling exposes fibers to the fiber-quality-reducing process of hornification, which is less pronounced in never-dried fibers [30–32]. More than 80% of respondents see fresh fibers and their higher quality as an asset (Figure 13). On average, slightly more than 10% of companies see an added value that is so great that it compensates for the occurrence of rejects (Figure 14). Both results are significant because it can be concluded that although virgin fibers from composite/laminate are seen as a value, the disadvantages are not compensated for. If one looks at the raw data, it is noticeable that the respondents who answered "agree" or "completely agree" (Figure 14) sort paper for recycling differently, and in some cases, not at all. The exact reason for the less critical view of the rejects cannot be determined from the data. However, differences in processing technology and competence in handling rejects are obvious.

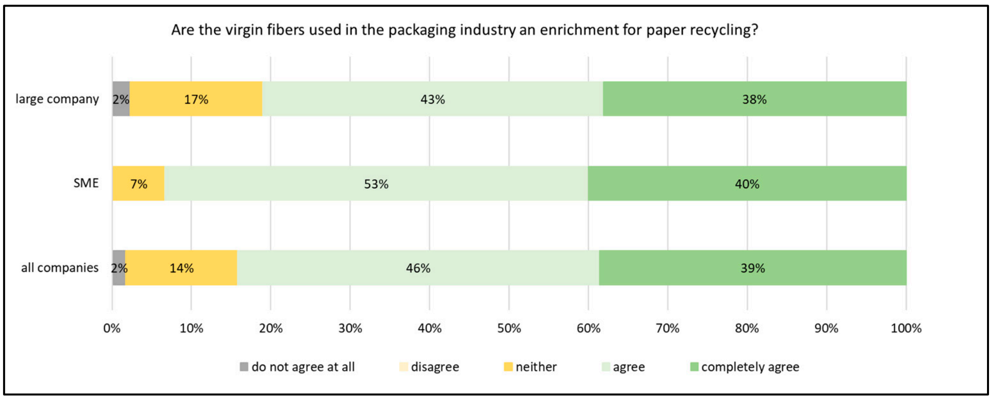

Figure 13. Value of virgin fibers from packaging (all companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise; "disagree" was not chosen).

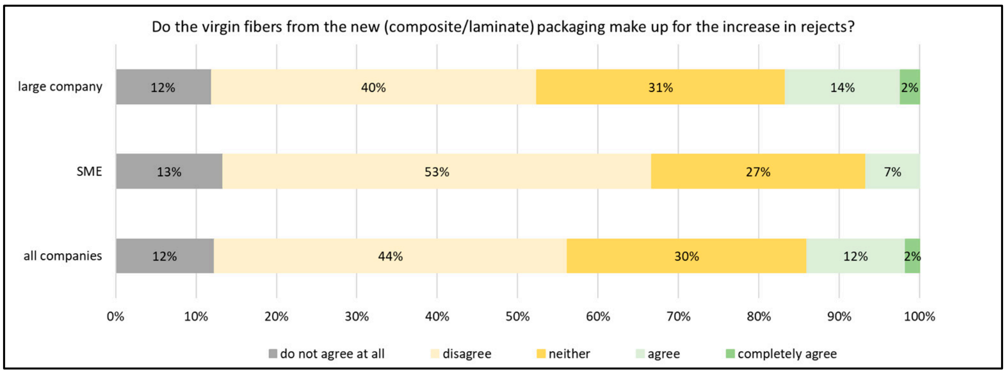

Figure 14. Comparison of value virgin fibers and rejects (all companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise).

The question of which paper for recycling causes problems is interesting (Figure 15). The biggest problems are caused by wet-strength papers. Wet-strength chemicals are polyamide epichlorohydrin (PAE), polyamidoamine epichlorohydrin (PAAE) and PET-based wet-strength chemicals [40–43,67]. Wet-strength chemicals increase the wet-tensile index, which is desired, and reduce repulpability as a side effect [41,42]. It is even reported that some paper mills "repulp wet strength agents containing materials by applying high pH, high temperature, and high shear with various levels of success" [42]. Such methods are well established in the paper industry but are mostly used in batch processes and for the known composition of wet-strength paper for recycling. Laminates with adhesive and plastic coatings also cause problems.

Adhesives, in general, are also critical. These are, for example, hotmelts, styrene–butadiene rubber, vinyl acrylates, polyisoprene and polybutadiene, and there are also pressure-sensitive adhesives, such as those used in paper labels [68,69]. Adhesives disintegrate during repulping, causing stickies [22]. Some of them can be removed by screening [69]. Mechanical methods do not remove all stickies; therefore, additives can be used to reduce the impact of stickies [70]. Stickies are tacky particles that adhere to processing machines and the paper, causing problems there such as web breaks [71]. Wax coatings are also critical. Wax can be applied as a water vapor barrier coating [45–47,72]. Adhesives and waxes can lead to stickies during paper processing.

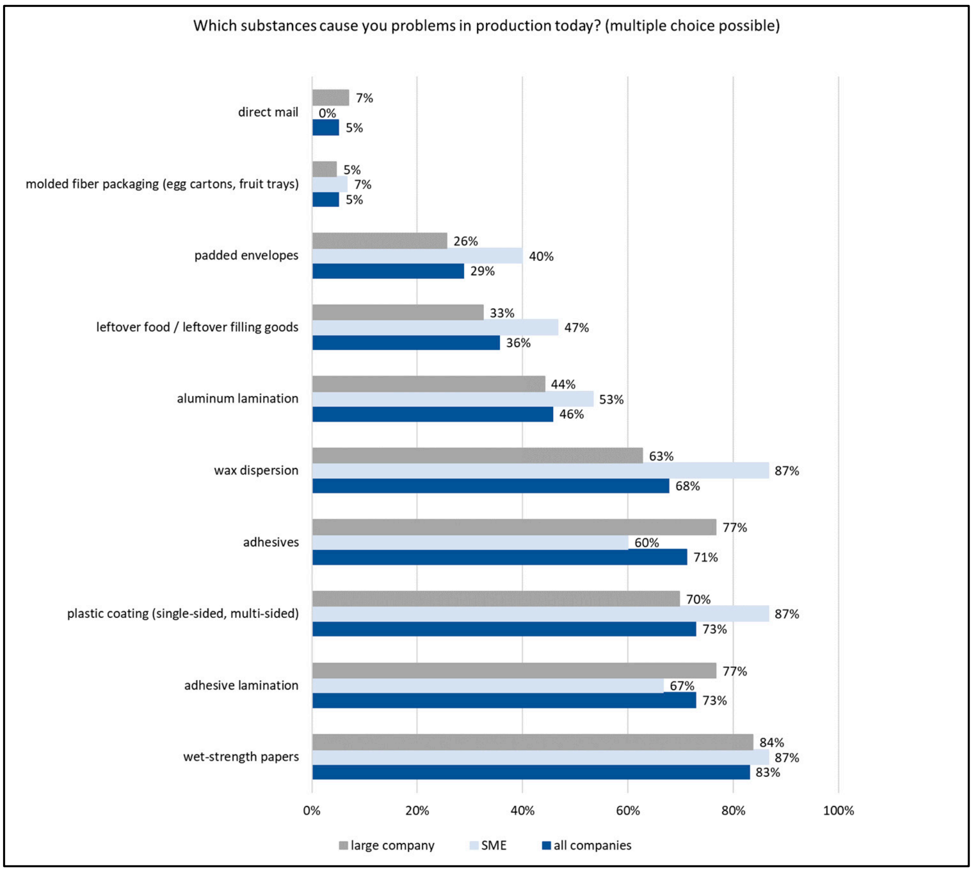

Figure 15. Causes of recycling problems (paper all companies n = 58, large companies n = 43, SME n = 15; SME: small and medium-sized enterprise).

Approximately one-third of the respondents reported problems with residues, e.g., from food, in the packaging, and in padded envelopes. Direct mail and molded-fiber packaging were hardly a factor. Residues, especially food residues, can be an issue because microbial growth is supported by food substrates.

If one summarizes the results, it is noticeable that adhesives, adhesive components and wax dispersions are seen as critical. Substitution by plastic coatings would also be viewed critically. The use of glued and plastic-coated composites/laminates will obviously increase due to the increasing use of fiber-based packaging, as will probably food residues in packaging. It is unclear to what extent fiber-based packaging will be fed into paper recycling. Due to license fees for dual systems (for consumer packaging), this packaging must be disposed of with the packaging waste. In this case, separate sorting and recycling takes place, which would have no effect on conventional paper recycling. To be expected are complex reactions in the process water, such as microbial growth and interaction and precipitation/deposition by undesired reactions with calcium ions from often-used calcium carbonate [73]. However, minerals such as calcium carbonate are also reported to bind and immobilize stickies [74].

The dwell time in the pulper was up to 10 min for 80% of respondents and up to 20 min for slightly less than one-third of graphic papers (Figures 16 and 17). When analyzing the raw data, it was noticeable that the companies that reported no problems with laminates and wet-strength papers (see Figure 15) frequently reported dwell times of up to 5 min. When developing composites/laminates, it should be noted that they should be able to be fiberized within 5 to 10 min in order to be reprocessed at 50% to 80% of recycling mills. However, a longer dwell time probably has no significance for the behavior of coatings. Longer dwell times during the dispersion of fibers during repulping require more energy [75]. Therefore, shorter dwell times reduce energy consumption during recycling.

A dwell time ("pulping time") reported in the literature is 15 min to 30 min [22,24] and 10 min to 20 min at 20 °C [76].

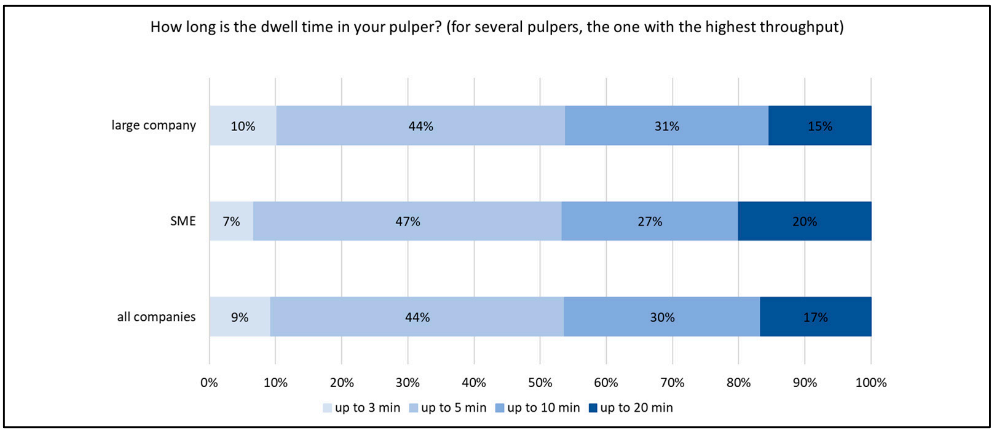

Figure 16. Dwell time in the pulper in relation to all the paper produced (companies n = 54, large companies n = 39, SME n = 15; SME: small and medium-sized enterprise).

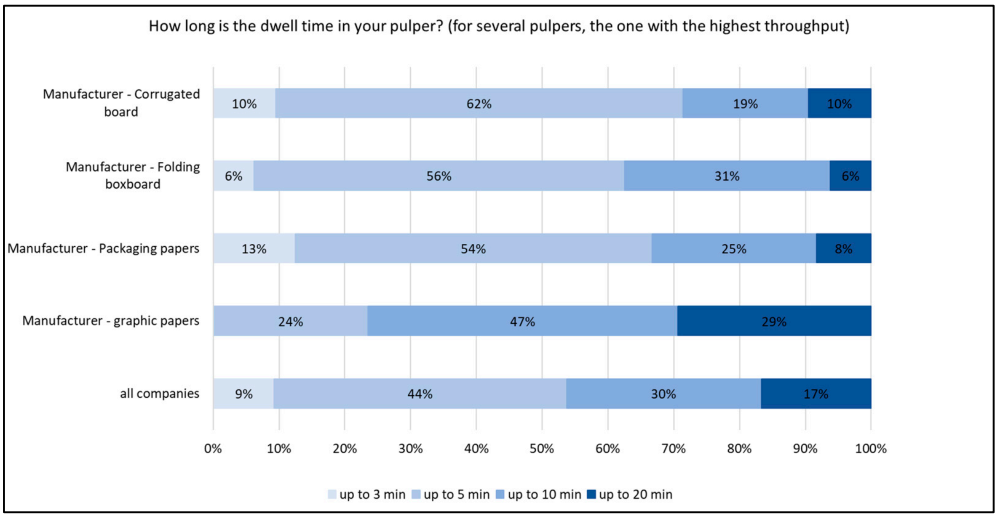

Figure 17. Dwell time in the pulper in relation to the produced paper (manufacturer-corrugated board n = 21, manufacturer-folding boxboard n = 16, manufacturer-packaging papers n = 24, manufacturer-graphic papers n = 17, all companies n = 54; one company can produce several products).

The companies were asked unsupported, open-ended questions about which topics were currently of most concern to them (see Supplementary File, S5). In addition to the topic of recycling, the aim was to identify important challenges facing the industry. The question was worded as follows: 'What problems are you currently most concerned with in your industry?' A total of 38 respondents answered. The following topics and problems were named: 14 respondents, energy; 9, raw material availability; 4, raw material costs; 3 respondents each, raw material quality, rejects and reject flows, uncontrolled content of hot melts, waxes and coatings; 2 respondents each, stickies, decarbonization, polystyrene and sales problems; 1 respondent each, spare parts, shortage of skilled labor, shortage of personnel, disposal, CO_2-neutral energy supply, certified end products, measuring method for checking recyclability, process water pollution due to plastic substitute formulations, through-dyed papers, wet-strength components, shredding of impurities, microbiological acidification, strength level, moisture content, non-degradable printing processes and water consumption.

Aggregating the results, the topic of raw material quality, impurities in paper for recycling and problems with recycling was mentioned 21 times; the topic of energy and decarbonization, 17 times; raw material availability and costs, 13 times. This shows that the topic of recovered paper quality is one of the most important issues in the paper industry, alongside the topics of energy costs and raw material availability. Energy consumption is relevant because paper drying is energy-intensive. However, recycling saves energy for producing virgin fiber pulp [22]. Surprisingly, per- and polyfluoroalkyl substances (PFAS), mineral oil and bisphenols were not mentioned in this survey by companies, even though such substances are substances of concern found in recycled paper as a non-intentionally added substance (NIAS) [77–84].

4.3. The Importance and Influence of Legislation

One important question is whether recycling-related legislation, innovations and trends have an influence on the quality of paper for recycling. Paper composites and laminates behave differently in recycling than conventional paper. Almost 90% of respondents stated that the quality of paper for recycling changes regularly, depending on legislation, trends and innovations (Figure 18). New developments and changes in the composition of recovered paper are empirically perceptible. However, only around 40% of graphic paper manufacturers agree with this statement (Figure 19). This indicates that graphic paper manufacturers base their paper for recycling procurement on targeted sources.

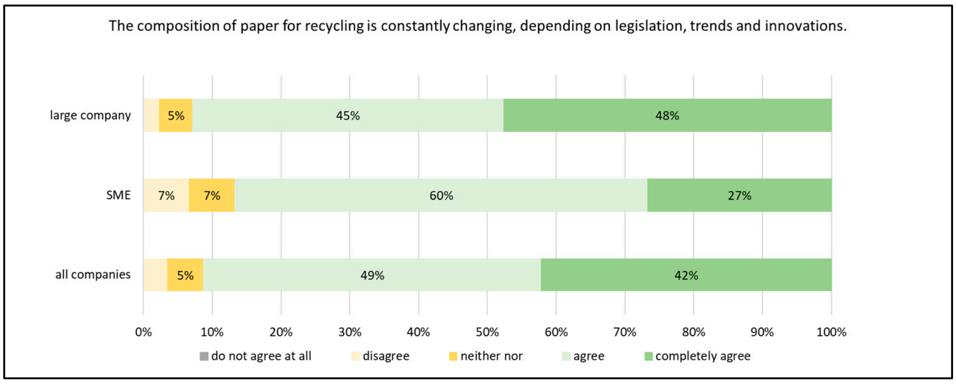

Figure 18. Changes in paper for recycling composition in relation to all paper produced (companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise; "do not agree at all" was not chosen.).

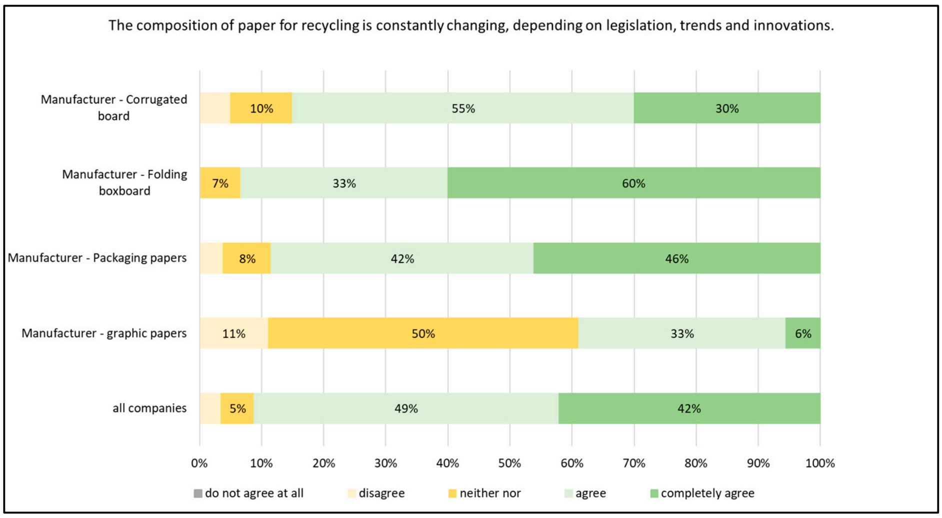

Figure 19. Changes in paper for recycling composition in relation to the paper produced (manufacturer-corrugated board n = 20, manufacturer-folding boxboard n = 15, manufacturer-packaging papers n = 26, manufacturer-graphic papers n = 18, all companies n = 57; one company can produce several products; "do not agree at all" was not chosen.).

Around 50% to 60% of the responding companies stated "agree" and "completely agree" that current legislation has an influence on the quality of recovered paper (Figures 20 and 21). This figure is lower than the number of responses to the question of whether recovered paper for recycling quality is changing (Figures 18 and 19). This shows that legislation has a significant influence on recovered paper quality, but that trends and innovations play a role regardless of legislation. From this, it can be concluded that changes in paper for recycling quality should be taken into account by the legislator, but that this does not explain all quality changes.

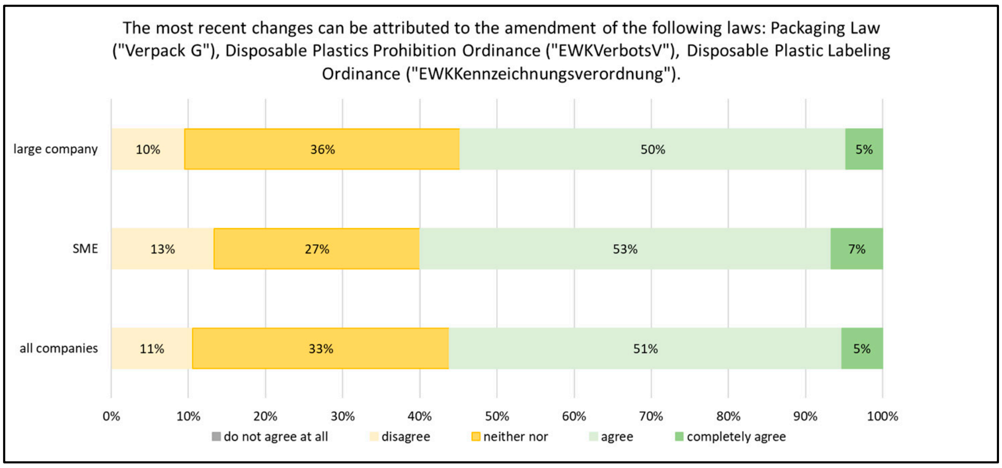

Figure 20. Influence of legislation on paper for recycling composition in relation to all paper produced (companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise; "do not agree at all" was not chosen.).

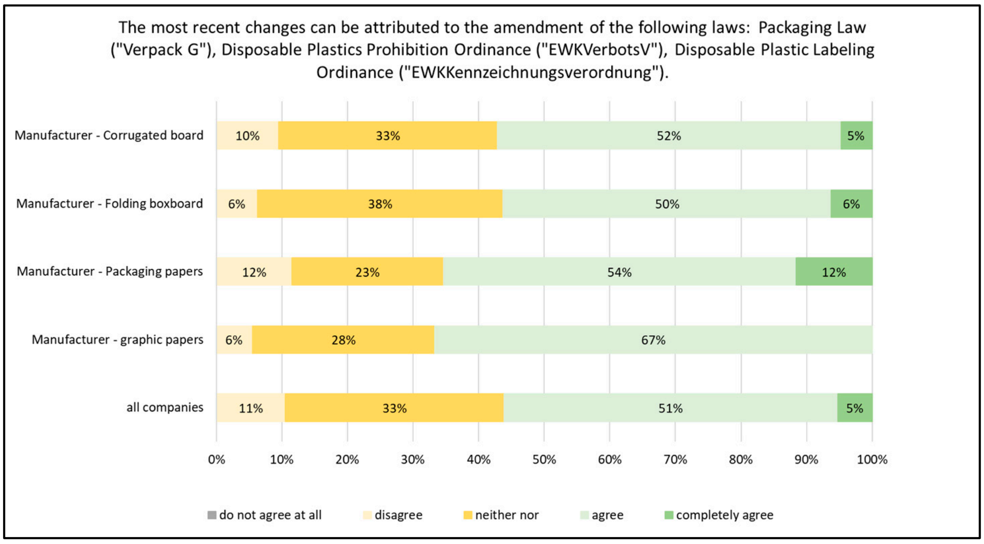

Figure 21. Influence of legislation on paper for recycling composition in relation to the paper produced (manufacturer-corrugated board n = 20, manufacturer-folding boxboard n = 15, manufacturer-packaging papers n = 26, manufacturer-graphic papers n = 18, all companies n = 57; one company can produce several products).

Fifty percent to sixty percent of the responses indicated that fiber-based composites/laminates are increasing in recovered paper (Figures 22 and 23). This figure roughly corresponds to the number of responses that observe an influence of legislation (Figures 20 and 21). Both figures are, therefore, plausible. Interestingly, almost 90% of the manufacturer-folding boxboard with "agree" and "completely agree" stated that more fiber-based composites/laminates are being supplied. It is possible that fiber-based composites have a greater impact on the quality produced there. Fiber-based composites/laminates might further increase by ongoing innovations such as the paper bottle [44].

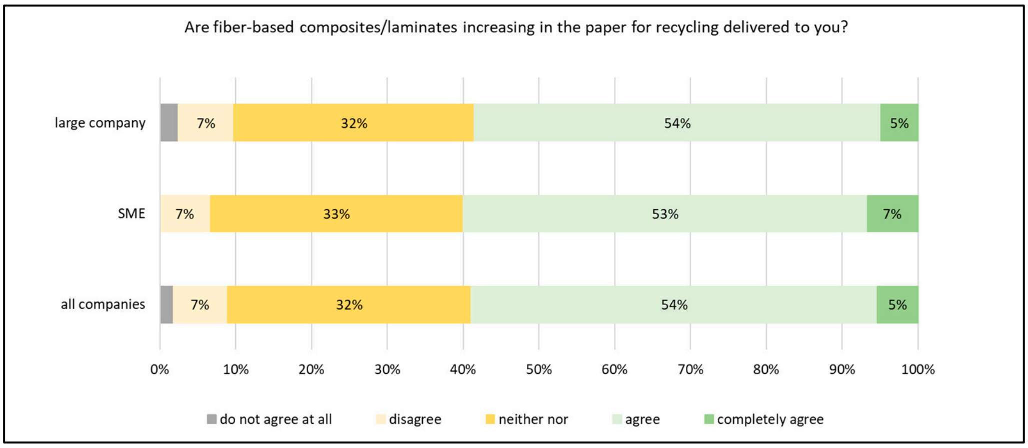

Figure 22. Increase in fiber-based composites/laminates in paper for recycling in relation to all paper produced (companies n = 56, large companies n = 41, SME n = 15; SME: small and medium-sized enterprise).

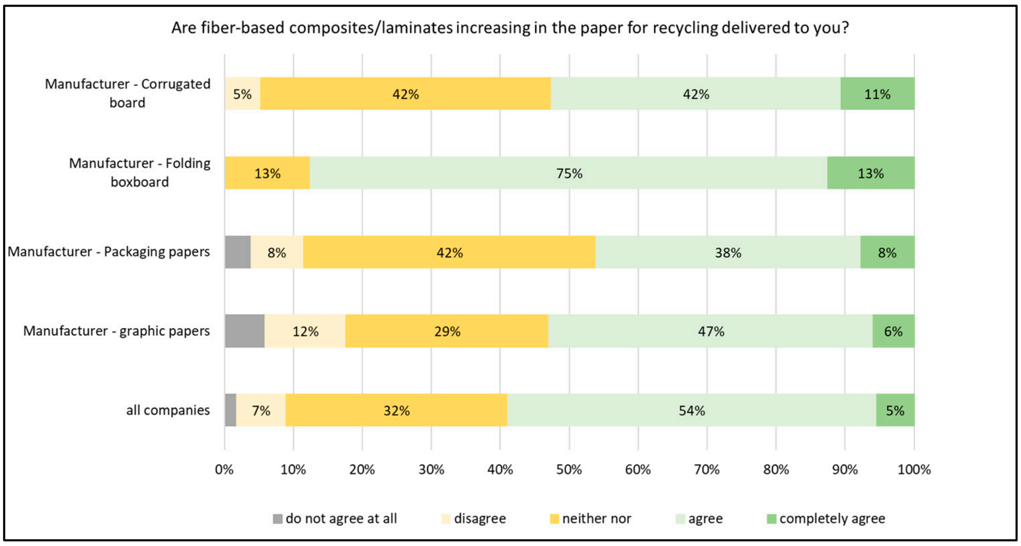

Figure 23. Increase in fiber-based composites/laminates in paper for recycling in relation to the paper produced (manufacturer-corrugated board n = 19, manufacturer-folding boxboard n = 16, manufacturer-packaging papers n = 26, manufacturer-graphic papers n = 17, all companies n = 57; one company can produce several products).

At present, in Germany, composite/laminate packaging must be disposed of via the packaging waste stream and not via the paper for recycling stream. Sixty percent of respondents agree that the fiber-based composites/laminates should also be disposed of via this waste stream (Figure 24). This result is relevant because, in the packaging waste stream, fiber-based packaging comes into greater contact with residues from other packaging in the plastic stream, and material transfers can take place. This reduces the fiber quality. Beverage carton packaging already contains food residues, e.g., from juice and dairy products [85,86]. Reported are 0.43 mL to 14.7 mL residue of milk in various 1 L beverage carton packaging materials [87]. However, results are from laboratory experiments, and these values are not gained from waste packaging. Another researcher reports 0.5% to 4.5% dairy product residue in beverage carton packaging, also from a laboratory study [86]. The residual filling quantities in fiber-based packaging materials that are returned to paper for recycling would increase with the increased use of fiber-based composites/laminates for high-viscosity filling goods. In the case of plastic packaging, significantly higher residual filling quantities were found in the packaging when high-viscosity products were packaged [88]. As expected, the quantities of residual filling material were significantly lower for low-viscosity filling goods [88]. As fiber-based packaging is coated with plastics, the results mentioned for plastic packaging can, in principle, be transferred to fiber-based packaging.

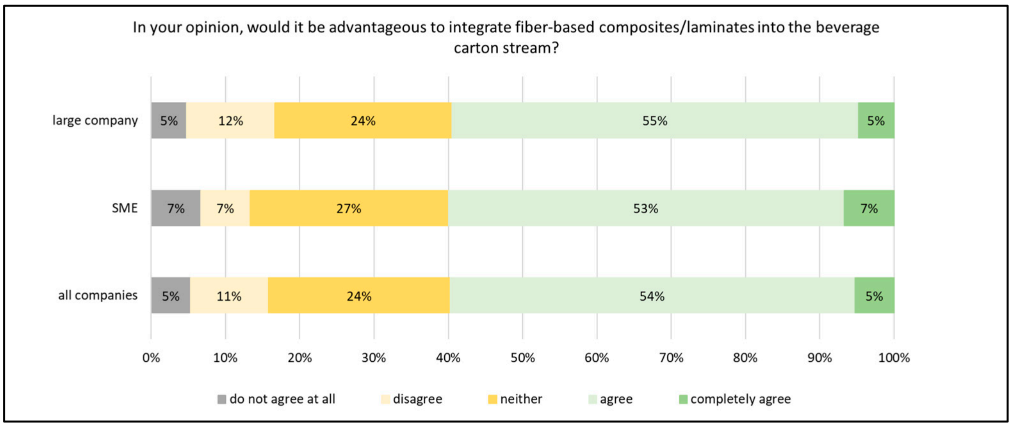

Figure 24. Integration of fiber-based composites/laminates in beverage carton stream in relation to all paper produced (companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise).

Beverage carton packaging might be shredded before recycling, improving the access of water and fiber dispersion [23]. This is done because the beverage carton is extrusion-coated with polymer from both sides, typically with PE-LD [89,90]. (To the authors' knowledge, beverage cartons are not always shredded before recycling). The fibers are valuable. From the companies' point of view, separate disposal is understandable because beverage carton packaging can contain around 20% plastic and around 5% aluminum foil [23,89,91], which increases the proportion of rejects. For incineration of rejects, pyrolysis and extrusion are proposed [92]. Around 75% of the weight is carton [93]. However, not all beverage carton packaging contains aluminum foil.

Fiber-based composites in the paper for recycling stream are considered problematic now or in the future by more than 90% (Figure 25). This result is remarkable because fiber-based packaging for food is usually made from virgin fibers of higher quality than recycled fibers. It can be concluded from this that when developing and implementing fiber-based composites (design for recycling, see Packaging Act-VerpackG), great attention must be paid to their recyclability, adjustments must be made to the recycling process management and technology and fiber-based packaging material should be separated and recycled separately.

One question that arises from the problems with fiber-based composites is the adaptation of the standards for paper for recycling, such as CEPI EN643 (see also German DIN EN 643:2014-11 [94]); 40% to 60% see added value in adapting the standardization of the classification of paper for recycling streams (Figure 26).

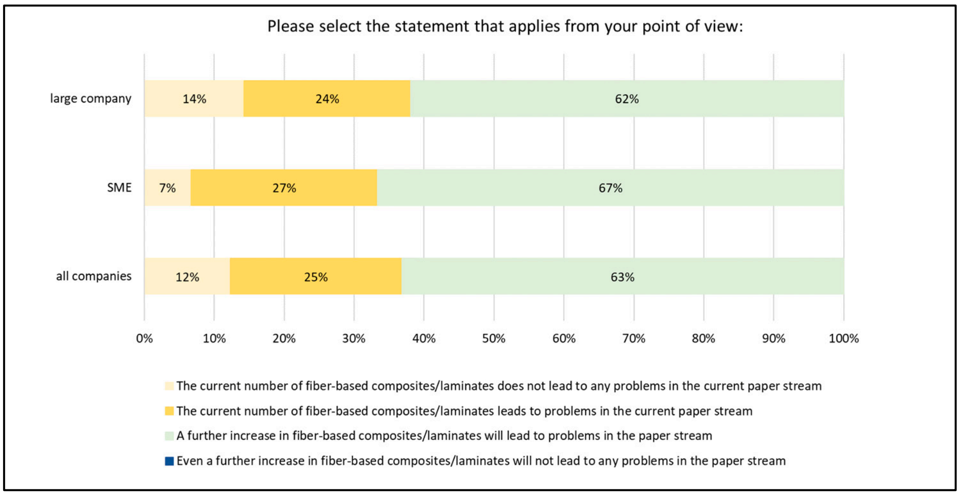

Figure 25. Problems with integration of fiber-based composites/laminates in beverage carton stream in relation to all paper produced (companies n = 57, large companies n = 42, SME n = 15; SME: small and medium-sized enterprise; "Even a further increase in fiber-based composites/laminates will not lead to any problems in the paper stream" was not chosen.).

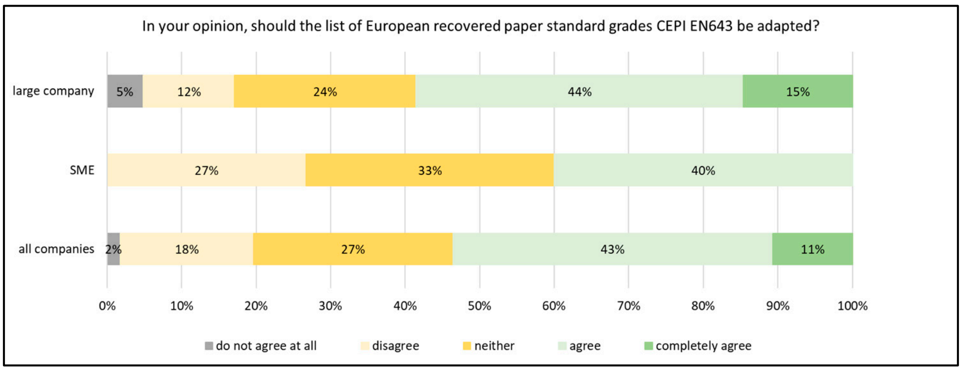

Figure 26. Evaluation of paper grade standard in relation to all paper produced (companies n = 56, large companies n = 41, SME n = 15; SME: small and medium-sized enterprise).

5. Conclusions

Paper for recycling from fiber-based packaging leads to challenges for recyclers in the production of newspaper, cardboard and corrugated board, and conventional stock preparation. Various types of coatings and adhesives, as well as wet-strength papers, are cited as problematic, and rejects are increasing. Although virgin fibers from fiber-based packaging are seen as valuable, they might not compensate for the disadvantages of coatings. An advantage of a longer dwell time in the pulper could not be derived from the raw data. Innovations, trends and legislation influence the quality of paper for recycling. Due to the current legislation and trends towards fiber-based composite/laminate packaging, problems are to be expected, from which a need for action is derived. Especially, an increase in fiber-based composites/laminates is expected. This will be reinforced by the plastic tax on virgin plastics, which is expected to be levied on the plastics industry in Germany in 2025. We can then expect to see an increased substitution of plastic packaging with fiber-based composites/laminates.

Some new technologies already exist that are able to solve the problem of pulping these special products. In order to achieve further improvements in the recycling rate and recycling results, there are various national and international projects dealing with this task and working on solutions (see European Association of the Paper Industry (Cepi)). Most important is that the developer of packaging material looks strongly to a design for recycling that is mentioned in different laws, regulations and guidelines, such as from

Cepi [95,96], and the minimum standard for the assessment of the recyclability of packaging is subject to system participation [62]. Regarding "plastic laminates", Cepi proposes, among other things, to "use only the required quantity of non-paper constituents", "the separation of the different elements should be as easy as possible", "Plastic lamination layers should not readily degenerate or break into very small pieces in the pulping stage.", "Optimise the adhesion between the laminate side and the board to facilitate separation.", and "If functionality allows, use material that is laminated on one side only" [95]. Another option might be to design packaging that requires little or no adhesives and is held together by the mechanical construction. As recyclability also depends on sorting, the available specific recycling technology and recycling infrastructure at companies, the usability of chemicals and contamination, e.g., with food, and economic aspects also play a role, the design for recycling is complex in practice. Nonetheless, it is to be expected that fiber-based composites/laminates will be more readily accepted for recycling if they are well designed and can be more easily recycled.

In the future, more research is needed on how well existing recycling test methods reflect the practice of the recycling industry and how fiber-based composites/laminates impact industrial recycling practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16156610/s1, Supplementary File with recycling paths, original version of survey and specific answers [97].

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