



## Improving the recycling of plastic parts in household appliances—a review

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### ABSTRACT

Household appliances account for a large proportion of the e-waste generated worldwide each year. Up to 75 % of this waste is currently incinerated or landfilled. The recycling industry focuses on harvesting valuable parts, like metals; however, household appliances are not only made of metals, but also recyclable plastics. This article reviews how the recycling of these plastics has developed since 2014 and which new approaches, such as eco-design, currently are being pursued to promote the recycling of (plastic parts in) household appliances in the future. The findings of the present review paper show that the consideration of recycling is extending to the life cycle of products over time; however, a holistic approach is still lacking, and although problems such as the recycling of plastics containing flame retardants are known, the latter are still not being considered in the product development phase. Other challenges, which already existed 10 years ago, such as those posed by the illegal sector, are still in focus today. Conversely, there are many ideas, like material tracking, incentive systems or microfactory treatment, on how the recycling of (plastic from) household appliances can be improved in the future, which necessitate further research.

### 1. Introduction

While the average number of people per household is decreasing in Europe, the overall number of households continues to rise (Eurostat, 2023a); likewise, the number of units of household appliances sold and disposed of is growing by 3–5 % annually (Jadhao et al., 2022; Allassali et al., 2020; Islam and Huda, 2019). According to the predetermined targets of the EU Directive (85 % recovered, 80 % at least recycled with large equipment), nearly all these units must be recycled one day (Directive 2012/19/EU). Given the published numbers of the European Parliament (2023), large household appliances make up at least nearly half (49 %) of the collected e-waste stream by weight in Europe (Chakraborty et al., 2022a), while an additional 10 % are made up by small household appliances (European Parliament, 2023).

Household appliances consist of base, heavy, and noble metals, plastics, glass, sometimes organic materials, and compounds (Itoh, 2014). The recycling of e-waste metals has already been frequently evaluated by previous review papers focusing on remediation technologies (Chakraborty et al., 2022a), future demand (Deetman et al., 2018), and urban mining opportunities (Mudali et al., 2021). However, to date, no review exists that focuses on the recycling of plastic in household

appliance waste.

This paper concentrates on the recycling of plastics from household appliances. The groundbreaking review paper by Buekens and Yang (2014) analyzes the status quo of e-waste plastics. To find out whether anything fundamental has changed in the recycling of plastics from household appliances waste since 2014, this review focuses on the following questions:

1. Which recyclable plastics are used in household appliances?
2. How are the plastics from household appliances currently recovered and recycled, and what are the challenges?
3. Which approaches exist to improve the circularity and recycling of plastics from household appliances, and to what extent are these approaches implemented?

These questions will be addressed in the following literature review. To begin with, the essential theoretical background is described. Then, Section 3 describes the steps of review. The results, split into past, present, and future, are given in Sections 4, 5, and 6. The final section summarizes the key findings of the review.

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## 2. Theoretical background

*Household appliances* can be characterized by size and are often defined as small (like vacuum cleaners, coffee machines, electric shavers) (Lase et al., 2021) or large (like washing machine, freezer, dishwasher) (Van Moeseke, 2022). Those devices, together with non-household appliances, belong to the group of electrical and electronic equipment (EEE). The European Union rules the treatment of EEE waste (WEEE) by the WEEE Directive (Directive 2012/19/EU), which establishes not only guidelines for collection, shipment, treatment, and recovery, but also sets quotas to be met in each country.

Recycling, recovery, and re-use in the European Union are legally defined in the Waste Framework Directive (Directive 2008/98/EC). Recycling is described as “recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes” (Directive 2008/98/EC). Neither fuel processing and backfilling in landscaping nor energy recovery count as recycling. Waste prevention takes priority over recycling and seeks to reduce the quantity of waste, hazardous substances, and the impact on the surroundings. A form of waste prevention is to take future recycling into consideration while designing a product. Although product design is mentioned in the WEEE Directive, it has a subordinate role.

Ecodesign is an approach to reduce the negative environmental impact of a product during its lifetime (Rossi et al., 2016). The impact on the environment is measured in categories using various analysis tools like Life Cycle Assessment (LCA). The categories usually differ; however, emissions with an effect on global warming and toxicity are generally considered (Rajendran et al., 2013). Different scenarios of state-of-the-art recycling technologies were investigated and showed that landfill is the worst option when it comes to overall environmental impact. Yet, burning plastics and printed circuit boards (PCBs) from large appliances has the highest impact on global warming (Ikhlayel, 2017).

Although the ecodesign approach already existed in the USA, Japan, and Australia before the turn of the millennium (Diehl et al., 2001), it experienced an upswing with legislation in Europe, with which it is now usually associated. For energy-related products, the European Parliament established a framework for the setting of ecodesign requirements with the Directive 2009/125/EC, which aims especially for energy and water efficiency (Your Europe, 2023). Even if the energy consumption of these products during use is significantly higher than during production or recycling (Lynch and Serrenho, 2023), ecodesign goes beyond the consideration of energy efficiency.

Specific ecodesign principles focus on the individual stages of the life cycle, so that product design is specifically geared towards repair, for example. (Van Doorselaer, 2022). In the context of product design, the Ellen MacArthur Foundation identifies four key levers for moving from a linear to a circular economy: The power of the inner circle, circling longer, cascaded use, and pure circles (MacArthur, 2013). In addition to LCA, tools such as the LiDS-Wheel or the Eco-Star are used to measure the implementation of the Ecodesign principles (Van Doorselaer, 2022). Case studies on the application of ecodesign principles for household appliances show that improvements in efficiency, particularly in the use phase of washing machines, dryers, and refrigerators, offer potential reductions of up to 40 %, for example in fossil resource depletion (Hischier et al., 2020). The remanufacturing of household appliances can also be significantly improved through changes in product design, such as the replacement of connection types (Kang et al., 2020).

## 3. Methodology

A systematic approach was chosen to conduct an in-depth literature review following the approach outlined by Palmatier et al. (2018). Included in this paper are all review articles that address e-waste recycling practices with focus on household appliances, the technology,

regulatory boundaries, and future developments, and which were published after 2014. 2014 was considered as the baseline year, as most household appliances have a life span of 7 to 10 years (Huang et al., 2020; Khan et al., 2019). Therefore, a newer generation of appliances has been recycled and recovered since then until today, which consequently may lead to changes, making an update appropriate. Scopus and Google Scholar were used as search engines to compile the database of articles.

The development from the research questions to the search terms is shown in Fig. 1. The three most important specific types of household appliances were used, in addition to “household appliances,” as described in Van Moeseke et al. (2022) and Lase et al. (2021). Regarding Google Scholar, the search was limited to an “all-in title” search, as it was not possible to search within the title, abstract, and keywords as with Scopus. Due to the given limitations in the search, there is a risk that articles have been excluded that are nevertheless thematically related to the topic under discussion, such as the article by Liu et al. (2023), for example, which addresses the recycling practice of e-waste and associated challenges but does not focus on plastics.

The search was limited to articles in English. Although the focus in this paper is on the European Union, the search is not limited to Europe, as problems in other parts of the world that may be caused by European devices as well as best practice solutions from other countries should not be excluded. The cut-off date of literature retrieval was Apr. 14, 2024. As the research questions are broad in scope the search is limited to review articles which also helps to map the research area as completely as possible. Overall, 88 articles were found through Google Scholar (4) and Scopus (84). None of them was redundant. Further queries in databases such as Ebsco and OpenAire did not return any new information, which indicates that the developments in this subject area have been covered. The collected papers were compared to the study design. Therefore, the title, abstract, and conclusion were screened for relevance to the research questions. If a paper was not relevant, it was excluded; if it was relevant, it was read in full.

## 4. Past results–status in 2014

Plastics are the second most often used material in WEEE with rising share (9 % concentration in large, 48 % in small household appliances) (Buekens and Yang, 2014). The recycling of plastics from WEEE (WEEP) is important due to the contained hazardous substances like flame retardants (FR) or heavy metals, which could harm the environment if not treated properly (Sugumar and Nayak, 2014). However, those substances are a big problem when it comes to recycling because of their environmental risks (Wang and Xu, 2014).

### 4.1. Composition and additives

The most used plastic polymers for household appliances are: Acrylonitrile Butadiene Styrene (ABS), Polystyrene (PS), High Impact Polystyrene (HIPS), Polycarbonate (PC), Epoxy resins (as there are also circuit boards in household appliances), Polypropylene (PP), Polyphenylene Oxide (PPO (blend HIPS/PPE)), PC/ABS with up to six different plastic resins in only one device (Buekens and Yang, 2014; Sugumar and Nayak, 2014). Of the plastics mentioned, small household appliances mostly contain ABS (28 %), PP (20 %) and PS (8 %) or blends of those. For large cooling appliances it is PS (76 %), PP (8 %) and ABS (6 %) (Wang and Xu, 2014). Furthermore, additives are added to all plastics to optimize their properties for the desired application, “such as stabilizers (thermal and UV), antistatic agents, flame retardants, colorants, pigments, plasticizers, fillers, reinforcing glass or carbon fibers” (Buekens and Yang, 2014). In the past, the composition and proportions of brominated flame retardants (BFRs) in plastics in particular have been investigated, as these pose a particular challenge in the recycling and reuse of plastic parts potentially forming polybrominated dibenzodioxins and dibenzofurans when incinerated. The samples examined

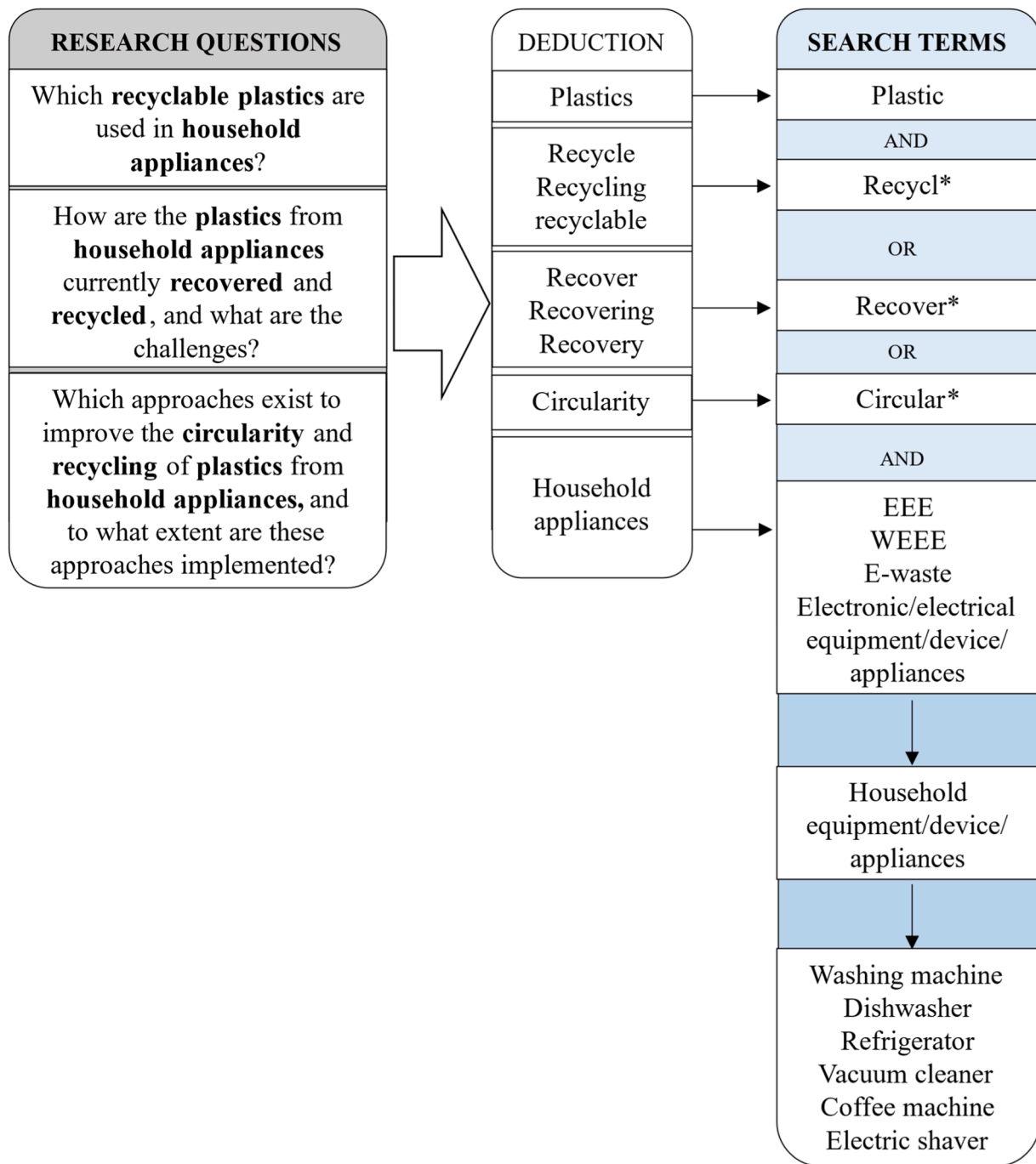


Fig. 1. Systematization and development from research questions to search terms with search terms derived from the same deduction being substitutes (operation OR), \* as placeholder and linking of terms (operation AND).

contained up to 28 % BFRs (Buekens and Yang, 2014; Wang and Xu, 2014).

#### 4.2. Sorting and identification

First, hazardous components are removed manually when e-waste is disassembled manually or shredded. Then, the remains are separated mechanically (Buekens and Yang, 2014). Manual dismantling is cost-intensive though it achieves the best yield in plastics recovery. Often, shredding is optimized for recovering the metal components; the remaining plastics are not suitable for recycling due to different kinds of plastics and foreign matter. For further recycling, the plastics need to meet a certain level of purity. Therefore, they are separated by different

methods like shape or density separation, still having the problem of foreign matter like wood parts. In 2014, there were innovative methods like froth flotation or optical sorting; however, those were not much in use.

#### 4.3. Recycling methods

After separating, there are different recycling options (Fig. 2). The standard method since the 1970s is mechanical recycling, where the plastics are regranulated and sold as recyclate (Buekens and Yang, 2014). For mechanical recycling, the thermoplastics should not only be separated by type (Buekens and Yang, 2014), but coatings and colors should also be removed, which can be achieved through grinding or

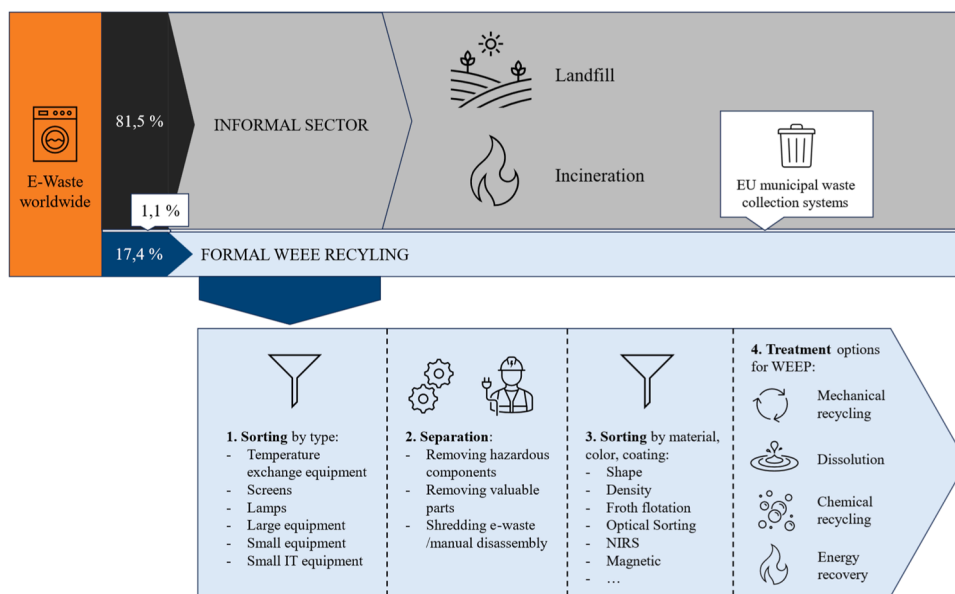


Fig. 2. Shares of WEEE in formal/informal recycling and municipal waste collection systems in 2019 and process steps of formal WEEP recycling until 2024. Data from: Buekens and Yang (2014), Van Yken et al. (2021), Jadhao et al. (2022).

Table 1

Numerical changes from 2014 to 2022 on global e-waste. Data from: <sup>1</sup>Van Yken et al. (2021), <sup>2</sup>Baldé et al. (2024), <sup>3</sup>Jadhao et al. (2022).

Changes in... on...	2014	Growth	2019	Growth	2022
Global e-waste recycling rate in wt%	17.0 <sup>1</sup>	→ + 0.4 %	17.4 <sup>1</sup>	→ + 4.9 %	22.3 <sup>2</sup>
E-waste generated globally in Mt	44.4 <sup>3</sup>	→ + 9.2 (20.7 %)	53.6 <sup>3</sup>	→ + 8.4 (15.7 %)	62.0 <sup>2</sup>
Global e-waste recycled in Mt	7.6 <sup>1,3</sup>	→ + 1.7 (22.4 %)	9.3 <sup>1,3</sup>	→ + 4.5 (48.4 %)	13.8 <sup>2</sup>
E-waste generated globally in kg/capita	6.4 <sup>3</sup>	→ + 0.9 (14.1 %)	7.3 <sup>3</sup>	→ +0.5 (6.9 %)	7.8 <sup>2</sup>

abrasion (Sugumar and Nayak, 2014).

Though legally not counting as recycling method, energy recovery is often applied when it comes to e-waste plastic recycling (Buekens and Yang, 2014; Wang and Xu, 2014). This could lead to several toxic components being released into the environment (Wand and Xu, 2014).

Dissolution (e.g., CreaSolv®, Vinyloop®) and chemical recycling via pyrolysis or gasification are further methods for recycling, yet due to product complexity, hardly in commercial use (Buekens and Yang, 2014; Sugumar and Nayak, 2014). Pyrolysis is regarded as better option compared to incineration as the contaminants are sealed in the process, generated in the residue, and gas emissions are reduced. In the light of environmental impact, neither incineration, pyrolysis, solvolysis, nor gasification is a good option (Wang and Xu, 2014).

#### 4.4. Challenges

The major challenge regarding WEEP recycling is “to separate the plastic types and identify additives and contaminants” (Buekens and Yang, 2014), especially BFRs (Sugumar and Nayak, 2014). Additionally, the treatment of exported WEEE by untrained workers who expose themselves to health risks and the accompanying threat to the environment is a problem (Sugumar and Nayak, 2014; Wang and Xu, 2014). Also, labeling export “waste trafficking” as sixth step in the waste hierarchy should be avoided (Bartl, 2014).

### 5. Present results–status until 2024

A comparison of the figures from 2014 to today is provided in Table 1. The global generation of e-waste increased to 53.6 million tons in 2019. It contained 17.4 million tons of small equipment and 13.1 million tons of large equipment, which corresponds to more than half of the e-waste generated. Up to 20 % of this was illegally transported and caused approx. 98 million tons of CO<sub>2</sub> due to poor recycling practice. Reusing and recycling of metals and plastics from WEEE, on the other hand, saved 15 million tons of CO<sub>2</sub> globally in 2019 compared with the use of virgin materials (Jadhao et al., 2022; Van Yken et al., 2021).

#### 5.1. Composition and additives

Nowadays, plastics are still the second largest used material in EEE with 10 to 30 wt%. (Jadhao et al., 2022; Akram et al., 2019). Especially household appliances include even 10 to around 50 wt% of plastics; overviews are shown in Fig. 3 (Al-Salem et al., 2022; Jia et al., 2022). The most common used are HIPS and ABS with 55 wt% of all WEEP followed by PP (20 - 30 wt%) and PC (approx. 10 wt%) (Al-Salem et al., 2022; Van Yken et al., 2021).

There are over 15 additional kinds of WEEP like e.g. Polyethylene, Polyoxymethylene, and Polyamide (Van Yken et al., 2021; Grigorescu et al., 2019). Due to the complexity of EEE, the number and kind of plastics vary with the product and its function, leading to up to 10 different kinds of plastic in large cooling appliances and 13 in small

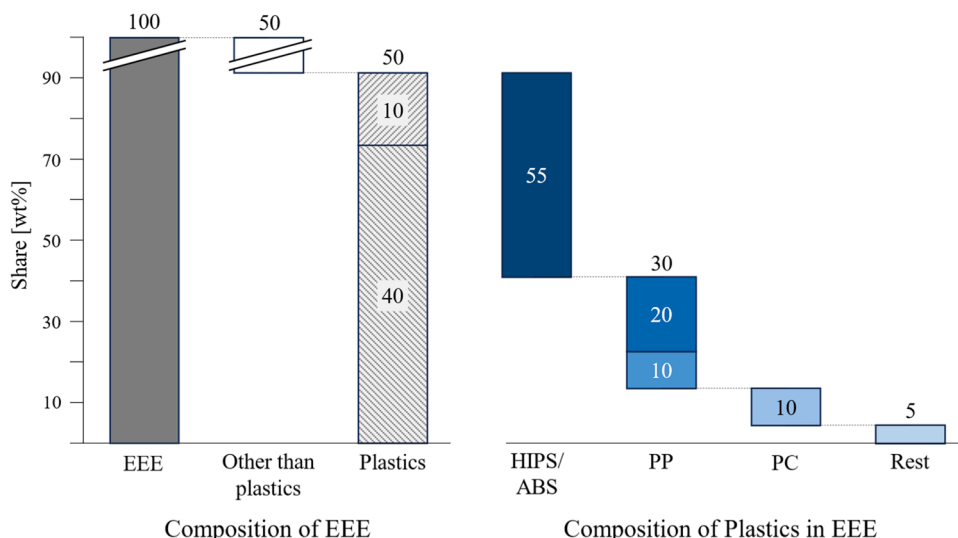


Fig. 3. Composition of EEE and the specific plastic types in EEE in wt%. Data from: Al-Salem et al., (2022), Da Silva Müller Teixeira et al. (2020), Jia et al. (2022).

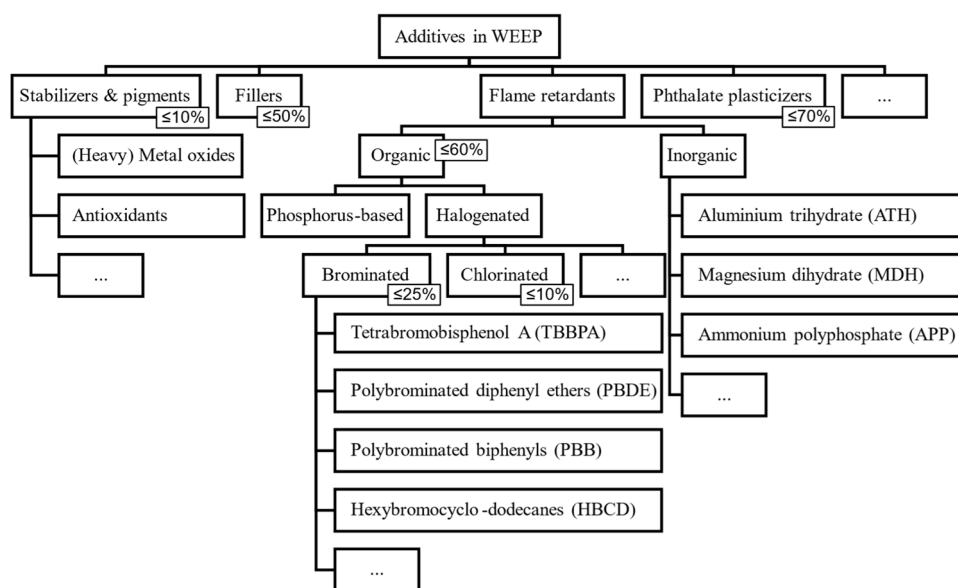


Fig. 4. Differentiation of additives and its wt%-share in WEEP (Tsuchimoto and Kajikawa, 2022; Delva et al., 2018; Jadhao et al., 2022; Al-Salem et al., 2022; Barouta et al., 2022).

appliances (Jadhao et al., 2022).

Additives to the plastics change characteristics like color or flammability (Jadhao et al., 2022) while at the same time limiting their recyclability due to a high level of toxicity (Barouta et al., 2022). Around 30 % of WEEP contain FR (Al-Salem et al., 2022; Tsuchimoto and Kajikawa, 2022).

The group of FRs divides into organic and non-organic with the commonly used type of over 75 different BFRs being organic (Ma et al., 2016). With the chlorinated FR, they belong to the group of halogenated FRs with a share of approximately 41 % in WEEP FRs (Jadhao et al., 2022; Tsuchimoto and Kajikawa, 2022). 60 % of those BFRs is Tetrabromobisphenol A, which is often used in household appliances (Fig. 4) (Al-Salem et al., 2022; Jia et al., 2022).

Due to the Stockholm convention, plastic containing BFRs cannot be reused, so when recycling WEEP, the absence of BFRs in the recycle must be ensured, which is not easy (see 5.2) (Sahajwalla and Gaikwad, 2018; Malkoske et al., 2016). The introduction of alternative, potentially dangerous FRs can lead to a vicious circle of removal and replacement

(Chainé et al., 2022; Sharkey et al., 2020). Another common application for FR in household appliances are PCBs, with FR not being the only hazardous component contained (Van Yken et al., 2021; Akram et al., 2019).

Other than FR, phthalates are used for plastic softening, as well as polychlorinated biphenyls, lead, other heavy metals, chlorofluorocarbons, hydrochlorofluorocarbons and pigments, which all have negative impacts on human health and the environment (Jia et al., 2022; Akram et al., 2019). Additionally, in household appliances, the probability of finding mineral fillers like talc, glass fibers or calcium carbonate is high (Da Silva Müller Teixeira et al., 2020).

### 5.2. Sorting and identification

There are two stages of sorting when it comes to WEEE recycling: Product sorting prior to dismantling and material sorting after dismantling. Before dismantling, the products usually are sorted by type to simplify recycling afterwards (Van Yken et al., 2021). After dismantling,

as there are several different materials and substances used in EEE, they must be separated for recycling (Chakraborty et al., 2022b), which leads to increasing process costs (Tsuchimoto and Kajikawa, 2022).

Identification of material is an important part of an efficient recycling process as complexity and additives complicate recycling. For plastics, there is a polymer code system printed or molded into the product. However, this does not ensure safe identification of the plastic type. Thus, there are several different techniques used to separate and therefore identify the WEEP and its properties. The techniques can recognize and distinguish for example the molecular weight, structure, the polymer morphology, thermal, or physical properties (Da Silva Müller Teixeira et al., 2020; Grigorescu et al., 2019).

Sieving, gravity separation, magnetic separation, electrostatic separation, cathodic electrodeposition, differential scanning calorimetry, and froth flotation (Al-Salem et al., 2022; Chakraborty et al., 2022b; Grigorescu et al., 2019) with automated specific gravity separation are the most common used techniques for sorting the different materials of WEEE (Tsuchimoto and Kajikawa, 2022).

However, in addition to the standard methods, new methods have also been developed, which are briefly discussed below. With plastics, Fourier transform infrared spectroscopy and near-infrared spectroscopy (NIR) can distinguish between different chemical structures, tested on various WEEP (Da Silva Müller Teixeira et al., 2020; Grigorescu et al., 2019). NIR can also be used to detect FR, but not to differentiate between different FR (Delva et al., 2018). The detection of highly absorbent black material, multi-component items and dirty or labeled products is also problematic (Tsuchimoto and Kajikawa, 2022; Grigorescu et al., 2019). For the identification of BFRs and other impurities in plastics X-ray fluorescence spectroscopy, energy dispersive X-ray analysis or Raman spectroscopy can be used (Da Silva Müller Teixeira et al., 2020; Grigorescu et al., 2019).

### 5.3. Recycling methods

The first step of recycling is systematic dismantling, which is also essential for collecting WEEP (Chakraborty et al., 2022b; Van Yken et al., 2021). Most household appliances are recycled via shredding before separating the different materials (Al-Salem et al., 2022; Prata et al., 2019; Sahajwalla and Gaikwad, 2018). In Lin et al.'s (2022) opinion, manual dismantling is outdated. It takes more time than conventional recycling like shredding although a higher purity is achieved (Islam et al., 2022). Not all parts can always be separated manually, e.g., if they are glued or welded. In this case, the disassembly is carried out mechanically to disconnect materials (Van Yken et al., 2021).

Compared to virgin materials, mechanically recycled plastics are sometimes affected in their properties when reprocessed multiple times (Da Silva Müller Teixeira et al., 2020). After several cycles the polymers cannot be reprocessed via mechanical recycling any longer (Sahajwalla and Gaikwad, 2018). A decline in properties can be prevented by using mixtures, adding interfacial agents or virgin material (Da Silva Müller Teixeira et al., 2020; Grigorescu et al., 2019).

The various properties of polymers such as impact strength, tensile strength, tenacity, elongation at break, melt flow index, or glass transition temperature are checked via measuring. The literature mainly contains tests on recycled HIPS, ABS or mixtures of the two materials made from e-waste (Da Silva Müller Teixeira et al., 2020).

HIPS can be recycled mechanically without a serious decline in its properties like tensile and impact strength, strain to break, and Young's modulus up to nine times. Therefore, a re-application of recycled HIPS in electrical and electronic devices is possible. ABS and mixtures of ABS and HIPS on the other hand show a decline in thermal and mechanical properties like an up to 43 % strain to break compared to virgin material. Reusing the material thus depends on the intended purpose and is also conceivable to combine virgin and recycled content to replace at least part of the virgin material in production whilst ensuring to meet the needed properties (Da Silva Müller Teixeira et al., 2020; Grigorescu

et al., 2019). When it comes to fiber enforced plastics, most of them are recycled via mechanical recycling after grinding which inevitably leads to fiber breakage with acceptable mechanical properties up to 10 reprocessing cycles (Pegoretti, 2021).

As the life span of household appliances comprise several years, reprocessing of aged ABS and HIPS was conducted in one study showing not only a decline in properties but also a strong coloration towards yellow and brown enhanced when reprocessed (Signoret et al., 2020). Leading to a contamination of recycle by small amounts of aged material (Das et al., 2021; Signoret et al., 2020). Given a fast technology development and rapid consumption rates, "the practical obsolescent duration is far shorter than material fatigue cycle" (Lebbie et al., 2021; Zeng et al., 2017; Pérez-Belis et al., 2015).

The dissolution process CreaSolv® can separate highly pure polymers from BFRs and other foreign non-polymer matter (Van Yken et al., 2021; Da Silva Müller Teixeira et al., 2020). With processing ABS and ABS/PC, there is the potential to upscale. PP shows no significant difference to virgin material when recycled via dissolution (Grigorescu et al., 2019). Since CreaSolv® can handle polymer-metal composites it is possible to recycle PCBs (Van Yken et al., 2021; Sahajwalla and Gaikwad, 2018).

Chemical recycling methods are currently under research, not achieving an industrial scale, though some are found to be promising like the low temperature catalytic depolymerization KDV process or the Haloclean both converting plastics into fuel without forming dioxins (Van Yken et al., 2021; Sahajwalla and Gaikwad, 2018). Another promising method for the chemical recycling of e-waste is the use of supercritical fluids (Preetam et al., 2023).

### 5.4. Challenges

Around 75 % of all WEEE goes into landfills or incineration due to a lack of regulation, primitive recycling practice and economic efficiency (Das et al., 2021; Li et al., 2018; Chatterjee and Abraham, 2016). This is maybe biggest challenge related to WEEP recycling.

Some WEEE is not recycled correctly because consumers do not discard it separately for special WEEE treatment (Al-Salem et al., 2022). Another problem is the attempt to catch up with ever-advancing product designs of highly heterogeneous, miniaturizing, and complex compositions and construction as there is no such thing as Design-for-End-of-Life (Abdelbasir et al., 2020; Devasahayam et al., 2019; Sahajwalla and Gaikwad, 2018). Thus, poor product design is one main barrier for recycling WEEE (Islam et al., 2022).

Although collection rates may be high and therefore successful, recycling in the informal sector leads to releasing several hazardous additives to the environment by open burning or dumping through unskilled workers (Nandy et al., 2022). As a resulting effect, plastic parts are broken down into smaller fragments, leading to environmental pollution from microplastics, which is increasingly highlighted by literature (Prata, 2024; Shaaban et al., 2024; Yalwaji et al., 2022). Although the informal sector has an active reusing and repairing understanding, a waste management system is needed (Hoang et al., 2022; Zhang et al., 2022; Li et al., 2018).

## 6. Future directions—status as of 2024

The development of future e-waste depends on many factors, such as demand or design. However, following the trend, the amount of e-waste will continue to increase and could reach 110 million tons by 2050 (Parajuly et al., 2019). The treatment of e-waste is therefore predicted in various scenarios, ranging from "business as usual" with a decreasing formal e-waste collection rate to "aspirational" with a formal e-waste collection rate of 60 % (Baldé et al., 2024).

### 6.1. Composition and additives

Flame retardants (FR) are the most regarded problem in WEEE studies. Though recycling methods are developing, until now there is no effective recycling method for WEEP containing BFRs at industrial scale (Yang et al., 2024; Chaîne et al., 2022; Tsuchimoto and Kajikawa, 2022).

At high cost, 100 % of BFRs can be decomposed by supercritical fluids (Jadhao et al., 2022). For the solvolysis different solvents, especially bio-solvents have been found efficiently extracting BFRs from WEEP (Das et al., 2021). However, the use of volatile organic solvents could be dangerous (Li et al., 2018). Removing FR in microwave-assisted pyrolysis has been examined using catalysts or bromine absorbers with at that time insufficient result, being limited by economic aspects and a full detoxification (Das et al., 2021; Risco et al., 2021). Fast and slow pyrolyses are more efficient than standard pyrolysis when it comes to BFR WEEP recycling, though the yield depends on the properties of the plastic and procedure used (higher yield on HIPS rather than ABS) (Ma et al., 2016).

Chaîne et al. (2022) suggest evaluating the regulative requirements for flame retardants to either eliminate all hazardous elements and/or allow building EEE without using flame retardants due to other fire warning measures. Their long-term solution is to find materials that make using flame retardants obsolete other than establishing effective processes. Tsuchimoto and Kajikawa (2022) assume that BFRs will remain the predominant FR, as no safe yet effective FR has been found to date.

### 6.2. Sorting and identification

Improvements in identifying the type of plastic and its grade relate to both the product or material to be identified and the technology used to identify it. For products, identification of plastic (grades) could be done via fluorescent markers, regardless of the WEEP color (Sahajwalla and Gaikwad, 2018).

The process of electrostatic separation, which is difficult because no more than two types of plastic can be separated at once and the efficiency depends on the humidity, could be improved by making several runs in series. Another technology, laser-induced breakdown spectroscopy, has recently become interesting for the recycling of WEEP due to its ability to recognize different types of plastic (PE, PP, PS, PET, PVC) and bromine. Plastics must be selectively wetted for flotation separation which is also the biggest challenge in this process. Surface treatment using ammonia has been successfully tested lately for ABS and PC reaching over 99 % purity (Tsuchimoto and Kajikawa, 2022).

In the future, the quality of existing and currently investigated sorting processes in particular will improve in order to carry out a complete analysis of WEEE plastics and therefore reduce costs and achieve a higher yield and quality of recyclates (Grigorescu et al., 2019). A good example of this is the adjustment of the values for density-based sorting as proposed by Van den Eynde et al. (2024) after the cut-off date of literature retrieval.

### 6.3. Recycling methods

As mechanical recycling needs presorting of the materials, which is accompanied by higher process costs, tests are taken if blended WEEP can be recycled without sorting (Tsuchimoto and Kajikawa, 2022). Solvent-based recycling also appears to be promising for the recycling of unsorted or even multilayer plastics. The maximum installed plant capacity worldwide in 2022 for dissolution is about 8000 t/a. For the future 48,000 t/a are planned (Klotz et al., 2024). Since the sources of the literature analysis do not deal much with solvent-based recycling in the future, but the picture of the recycling possibilities of plastic from household appliances should be presented as completely as possible, a separate reference was used here.

Chemical recycling methods like the hydrothermal treatment, co-

pyrolysis or pyrolysis-catalytic upgrading is currently being tested demanding further research (Jadhao et al., 2022; Ma et al., 2016). Hydrothermal treatment is promising removing antimony from the plastic PCBs fraction (Das et al., 2021). Compared to pyrolysis, gasification has the advantage of processing different types of plastic at the same time, but it also consumes more energy and forms tar. Metal catalysts can reduce the formation, but further studies are needed for industrial use. The situation is similar for the use of supercritical fluids. But the installation, operation and maintenance of supercritical fluids technology is associated with high costs (Jadhao et al., 2022).

A new direction of research is regarding bioprocessing. In this process, bacteria, algae or other microorganisms are used to depolymerize plastics into monomers (Lee et al., 2024; Rambabu et al., 2023). Therefore, several microorganisms are used to degrade different kinds of polymers. HIPS, PE and LDPE were found to be successfully degraded up to 23 % in one month, with PE and LDPE taking more time than HIPS. Currently, it is not employed in a large scale (Van Yken et al., 2021). By using biological methods removing heavy metals from WEEE can be done, which has several advantages but being more costly than chemical processes (Chatterjee and Abraham, 2016).

The development of recycling methods is also driven by European Union legislation such as the Circular Economy Action Plan and the resulting regulations to reduce the environmental impact (Al-Salem et al., 2022; Barouta et al., 2022). In addition to improving and creating newer, more sustainable recycling methods, this also leads to a reduction in greenhouse gas emissions, which is the most environmentally sound method primarily assessed by LCAs and in particular CO<sub>2</sub> emissions. The literature on LCA shows that mechanical and chemical recycling are preferable to energy recovery and landfilling, e.g., in terms of acidification potential (Tsuchimoto and Kajikawa, 2022). Since the studies on the CO<sub>2</sub> emissions of the various recycling methods vary greatly due to the different e-waste input products (He et al., 2024), a source outside the literature analysis was used for the comparison. The CO<sub>2</sub> emissions in kg CO<sub>2</sub> eq per kg polymer of 25 plastics were determined using various recycling methods. In principle, mechanical recycling (closed loop) and dissolution resulted in the lowest emissions compared to incineration. For ABS, dissolution resulted in 1.8 and mechanical recycling in 2.0 kg CO<sub>2</sub> eq per kg ABS while incineration caused 7.8 kg. With HIPS, pyrolysis (monomers) had the lowest emissions with 1.7 kg CO<sub>2</sub> eq per kg HIPS, with PP it was gasification (monomers) with 1.0 kg CO<sub>2</sub> eq per kg PP (Schwarz et al., 2021). Nevertheless, the choice of method should not depend solely on this, as some recycling methods can utilize material that would not be possible with supposedly better rated methods. In addition, technical progress, for example through low-temperature pyrolysis or prior sorting methods, can lead to a different assessment (Tsuchimoto and Kajikawa, 2022).

### 6.4. Challenges (and potential future solutions)

As the biggest problem is the amount of WEEE being incinerated or landfilled, consumer behavior should change. Therefore, Pérez-Belis et al. (2015) suggest introducing incentives to encourage users to treat their e-waste properly. Also, a system could be introduced that encourages responsible purchasing for less impact on the environment and a better recyclability (Akram et al., 2019).

Together with a sustainable WEEE management, all parties participating in the material flow, from designers to recovery companies, could be connected and they could furthermore use the advantages of digitalization to implement a circular economy (Devasahayam et al., 2019; Mattos Nascimento et al., 2019; Li et al., 2018).

Often there are also suggestions to policy and regulations made (Zhang et al., 2022; Sharma et al., 2021; Prata et al., 2019). Akram et al. (2019) propose to take firm action against consumers and manufacturers not following the rules. Another suggestion addresses the need of material management with current regulations concentrating widely on a macroscopic level of products and components, less on a material-level

like ecodesign or green material and far too little on substances (Zeng et al., 2017).

Either way, drivers are needed to effect change and advance positive developments in waste management (Nichols, 2016). Helpful in those respects is the usage of Industry 4.0 technologies with databases and cloud computing to support the automation of reverse logistics, waste treatment and identification of substances so that products and materials are tracked and toxic substances from electrical appliances are not released into the environment (Barouta et al., 2022; Mattos Nascimento et al., 2019; Zeng et al., 2017).

### 6.5. New approaches

Not recycling the FR-containing WEEP but using it in a coarse form as concrete aggregates up to 10 % is an approach of the construction sector. Fly ash can be used as partial substitute for cement up to 25 % (Al-Salem et al., 2022; Van Yken et al., 2021; Luhar and Luhar, 2019). Nevertheless, using WEEP in concrete applications results in lower strength properties, only suitable for the use of non-structural and precast products (Rani and Senthil, 2023; Kaliyavaradhan et al., 2022). Advantages of using WEEP as a partial replacement for concrete are the weight, processability, durability, and the cost factor (Mtibe et al., 2023). However, the usage of WEEP in construction parts is not a circular application (Tsuchimoto and Kajikawa, 2022). Therefore, only WEEP that is not recyclable, such as the 30 wt% containing flame retardants, should be used for this cause (Tsuchimoto and Kajikawa, 2022).

Recycling in the future could be conducted in so-called micro-factories, being a decentralized, “lean, agile and customizable” technology, which “transform e-waste plastics into a completely new and higher value product rather than converting it back to a plastic product” (Sahajwalla and Gaikwad, 2018). Microfactories are going to transform PCBs into supercapacitors, carbon micro fibres and foams or sustainable composite panels (Mtibe et al., 2023; Sahajwalla and Gaikwad, 2018).

“Design-for recycling” and Extended Producer Responsibility (EPR) are two competing strategies associated with e-waste recycling” (Islam et al., 2022). EPR is a policy approach that enhances the producers’ responsibility until the end-of-life and final disposal (Chatterjee and Abraham, 2016; Pérez-Belis et al., 2015). Design-for-recycling, on the other hand, considers and therefore controls the recyclability of a product at early production stage before negative impacts are realized. Through this ecodesign measure, products become valuable sources of raw materials for which responsibility becomes less of a problem and an obligation than a desideratum. (Al-Salem et al., 2022; Barouta et al.,

2022).

Ecodesign also includes the need for re-designing and re-thinking existing recycling technologies, e.g., the screws of injection molders to ensure a better recycling of fiber enforced polymers (Pegoretti, 2021; Pérez-Belis et al., 2015). To help disassembly strategies, a modular design could be incorporated (Islam et al., 2022), supported by the new ecodesign regulation for the Right-To-Repair (Van Yken et al., 2021). As there are many reusable parts in WEEE, broken machines can be repaired with these parts to elongate their life (Akram et al., 2019). Also, there are some design rules concerning material compatibility, e.g., using mono-materials plastic, one type of plastic per product, recognition marks, limited stickers and ensuring easy separation of combined materials that are difficult to recycle (Akram et al., 2019; Zeng et al., 2017). For a better yield of recyclable material, design recommendations could be made according to material compositions (Van Yken et al., 2021; Pérez-Belis et al., 2015).

Additive manufacturing offers several advantages like on-demand production and design freedom (Islam et al., 2022). In addition, the suggestion is made to substitute the plastic by bio-based material (Chaine et al., 2022; Li et al., 2022; Akram et al., 2019).

Furthermore, a reduction of the number of different plastics used in EEE is proposed (Prata et al., 2019). A similar idea is the usage of polymer fibers to strengthen polymers for a full end-of-life recovery making recycling easier (Pegoretti, 2021). All these suggestions aim for the concept of circular economy with closing the loop using the R-principles (Al-Salem et al., 2022).

## 7. Discussion

Table 2 shows the comparison of the findings in facts and figures. The results of the first question showed that the types of plastic used in household appliances have not changed since 2014; however there are more types overall and more types per appliance, which makes recycling more difficult. The largest proportion by weight is recyclable with ABS, PP, and PC or PS. PCBs are also coming into focus, as they are installed in every electrical device, even if they only make up 3 to 5 wt% of the total e-waste. They consist of plastic, metal, and ceramic compounds and can now be disassembled at a rate of 94 %.

The second question deals with the recycling of these types of plastic and the associated challenges. The recycling process of household appliances has changed only marginally since 2014, as the development of new methods takes time to reach industrial maturity and there are no regulations on recycle usage quotas, which means that recycling WEEP is not worthwhile from an economic point of view. The appliances are

**Table 2**  
Comparison in figures and facts of changes in recycling plastic parts from e-waste from 2014 until 2024 with outlook based on the research results.

Comparison in figures and facts		Status		
		in 2014	until 2024	from 2024
Number of plastic types in Household appliances	Large Small	6	10 13	1
Concentration of plastics in Household appliances (in wt%)	Large Small	9 48	10 50	as little as possible, if there is still no possibility to an infinite recycling of WEEP
HIPS/ABS concentration (in wt%)		up to 13	up to 27	
PP concentration (in wt%)		up to 10	up to 15	
PS concentration (in wt%)		up to 7	–	
PC concentration (in wt%)		–	up to 5	
Share of WEEP with Flame retardants (in %)		–	30	Suggestion: 0 (Chaine et al., 2022)
Landfills or incineration of WEEP (in wt%)		–	up to 80	as little as possible
Number of mechanical recycling cycles without decline in properties	HIPS Fiber enforcement	– –	9 10	as much as possible (by e.g. redesigning screws of injection molders)
Amount of WEEP recycled (in wt%)		2	10	close to 100
Main recycling technologies used		Mechanical recycling	Mechanical recycling; dissolution	Mechanical recycling; dissolution; chemical recycling; bioprocessing
Main challenges		Separation and identification of plastics, additives, and contaminants; illegal exports	Informal sector; environmental pollution; heterogeneity of appliances	improper treatment; lack of regulation; poor product design

further on shredded to extract valuable metals, while the remainder is usually incinerated, see Table 2. Mechanical recycling of WEEP is still the focus.

The challenges involved in recycling (plastics from) household appliances vary in nature and change over the years (see Table 2). In 2014, recycling plastics from household appliances faced two main challenges. Firstly, the type of household appliances and the materials they contain, and secondly, the resulting informal exports and the associated environmental and health risks. The appliances themselves were not designed to be recycled, both in terms of their material and design composition. They contained hazardous substances that were prohibited by law for reuse but were released into the environment during informal recycling or disposal, accounting for 70 % of toxic substances in the environment (Chatterjee & Abraham, 2016). In addition, according to estimates, over 140 million tons of CO<sub>2</sub>-equivalent were released in 2022 because of low-quality recycling of collection group 1 appliances (Baldé et al., 2024). Until 2024 and beyond, the associated environmental pollution will be the focus of the challenges together with the heterogeneity of products and their design.

To solve these challenges and improve the circularity of household appliances, the third research question leads to possible new approaches for improvement and their implementation. The way of dealing with technology-related obstacles that impair recyclability, such as the separation of different plastics or the identification of additives, has improved significantly by 2024. There are identification and sorting methods for hazardous substances up to 100 % purity and new methods that either use biological organisms for degradation up to 23 % in one month or chemically break down polymers into monomers, although not yet in industrial application (Jadhao et al., 2022; Van Yken et al., 2021). Improved recycling options have also minimized the impact on the environment. Recycling the most common WEEP reduces energy consumption by up to 90 %, gas emissions by 87 %, and therefore the environmental impact during production by a factor of five compared to virgin material. In 2019, recycling of metals and plastics from WEEE saved 15 million tons of CO<sub>2</sub> (Jadhao et al., 2022; Van Yken et al., 2021). Alternative methods for recycling WEEP with a high degree of purity are a step towards more circularity. Nevertheless, there is no way around new approaches for recycling as the possibilities of mechanical recycling are finite. However, these must be critically evaluated in terms of their impact before they can be used on a large scale. The environmental impact of chemical recycling has not yet been fully investigated.

However, the recycled materials obtained must also find their way into the production of new products, which can be achieved through a legally prescribed recycle usage quota. The use of recycled materials in products reduces the environmental impact and at the same time closes the cycle, as long as the recycled materials are reused in the same appliances. Construction use, even if the substitution only amounts to 10 %, should be viewed critically, as this material is no longer available to the cycle. In addition, different materials are inseparably mixed, which could pose new problems when recycled at a later date.

The remaining problems of poor product design and illegal exports as well as the incorrect handling of WEEE must also be addressed through legislative changes. In contrast to 2014 where the upper levels of waste prevention and reuse of the waste hierarchy had no application in the core business of waste management, they are included in addition to recycling by 2024. Improvements such as ecodesign, which do not attempt to solve existing problems but instead consider the solution at the beginning of a product's life, are extensive but also holistic. This involves clear rules, such as avoiding different types of plastic in a product. Ecodesign measures can and must be supported by digitalization, more effective collection systems, and appropriate legislation all over the world such as the upcoming Ecodesign for Sustainable Products Regulation in the EU (European Commission, 2023). As ecodesign approaches that focus on more than just energy or water consumption have only recently come to the fore, and household appliances have a usage phase of 7 to 10 years (Huang et al., 2020; Khan et al., 2019), these

developments cannot be quantified yet. However, the energy efficiency measures of the Ecodesign legislation alone led to a saving of “28 % of the total annual electricity consumption of the average household in 2020” (European Commission, 2024). It can therefore be assumed that regulatory ecodesign measures to improve circularity will have a positive impact.

The proportion of properly recycled appliances must also be increased in order to be able to recycle more plastics from household appliances. If appliances are seen as a valuable source of raw materials in the future, if it makes sense for recycling companies to dismantle all parts, and if the economic viability is ensured by laws, for example on the use of recycled materials, illegal exports will become less interesting and at the same time a problem that must be tackled, for example through stricter controls.

If manufacturers follow the rules of ecodesign when designing appliances and treat their old appliances as a resource for new products, a change can occur. Even though there have been new technical developments since 2014 that make it possible to recycle WEEP, there is no industrial application yet. Together with a higher number of properly recycled devices, it is therefore reasonable to conclude that one key to the future recycling of plastic from household appliances resulting in the smallest possible negative impact on the environment lies in ecodesign, its implementation, and supporting regulations. Appropriate rules and legislation must be established and enforced in order to comply with the circular economy and its R-strategies.

## 8. Conclusion

This review contributes to a better understanding of the developments and challenges related to the recycling of plastic parts from household appliances since 2014. In the course of time, the consideration increasingly includes further life cycle phases and their effects on recycling in the improvement of recycling. While the focus in 2014 was still on mechanical recycling and improving sorting, the current focus is on the (further) development and testing of new recycling methods and the establishment of a sustainable circular economy by applying the R strategies. Each separate phase of the life cycle of a household appliance poses individual challenges for recycling. Solutions beyond the possibilities presented in this review will have to be found in the future with the aid of various methods such as ecodesign. Future research should address the issues described in this review from a technical, legal, and environmental perspective. However, the existing appliances and associated challenges should not be overlooked; postponing the problems into the future or possibly creating further recycling problems, e.g. by using them in building materials, is not a proper solution.

## CRediT authorship contribution statement

**Jule Jeschonowski-Papstein:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lukas Gast:** Writing – review & editing, Visualization, Supervision. **Markus Binding:** Writing – review & editing, Supervision. **Martin Faulstich:** Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

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

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