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Handle ID: .http://hdl.handle.net/10985/20696

To cite this version :

S.M. Mizanur RAHMAN, Stéphane POMPIDOU, Thècle ALIX, Bertrand LARATTE - A review of LED lamp recycling process from the 10 R strategy perspective - Sustainable Production and Consumption - Vol. 28, p.1178-1191 - 2021

A review of LED lamp recycling process from the 10 R strategy perspective

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Keywords:
Ewaste recycling
LED luminaire
10 R approach
Recycling recommendation

Recycling LED lamp technology requires a change from the traditional bulk material-based recovery process. Unlike preceding lighting technology, LED lamps cannot be recycled to meet the regulatory minimum recycling rate of 80% due to multi-materials, including small quantity precious metals, which reduce the sorting efficiency. Therefore, it is crucial to understand how the challenges have been approached in the scientific literature in this context. The review article investigates the circular solutions to the challenges that the end of life LED lamp management is facing. This review applies PRISMA systematic literature review to locate the relevant studies and investigate whether the proposed processes can increase the recycling rate, using the circular economy strategy as a theoretical framework. Several recycling processes have been proposed in the academic literature. However, the techniques have not been evaluated against the circular economy strategies to identify current gaps and possible ways. This review attempts to fill this gap by assessing the current approaches against the 10 R strategies (refuse, rethink, reconsider, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover). The study suggests that recycling is the dominant strategy, but the higher R strategies such as reuse, repair, and remanufacture have also been discussed as potential life extension strategies. The study concludes by proposing an integrated treatment approach that focuses on higher R's (reuse, repair, refurbish, remanufacture and repurpose) instead of focusing on lower R's (e.g., recycling).

1. Introduction

The circular economy (CE) has gained attention in businesses and academics. Despite disagreement in significant concepts, definitions, and theoretical origins, circular economy has been adopted in many developed countries and regions to initiate sustainable production and consumption (Reike et al., 2018). For example, China adopted several regulatory actions to promote CE at various levels. However, implementation challenges and ways to overcome them have not yet been resolved. Therefore, many studies simultaneously engaged in consolidating circular economy strategies and identifying challenges in each strategy. For example, Reike et al. (2018) conducted a review article on the different R-imperatives. They found that R-imperatives vary from 3Rs to 10Rs, in which 3-5Rs are dominant strategy with a clear hierarchy, as opposed to 10Rs strategy, which seeks to articulate nuances and maximize value retention . Potting et al. (2017) supports the adoption of 10R strategies, clearly identifying roles at the material, component, product, and production level. The strategy encompasses sustainable production to prevent waste generation and modify consumption style for a longer time. The 10R strategies have been further elaborated and contextualized from the production, use, and EoL phase through a circular strategy scanner, advancing the 10R strategies further (Blomsma et al., 2019). Morselletto (2020) focuses on adopting specific targets for each strategy, highlighting well-defined regulatory limits in favor of higher strategies. Thus, it is clear that discussion in circular strategies has been advancing through articulating and extending different aspects of 10R strategies. However, the hierarchies of preferences are not well defined and may substantially alter based on measurements of impacts of each strategy and trade-offs among the options for different product categories. Therefore, it is essential to establish the order by advancing the systematic discussion of these strategies in the context of various materials and product groups (Reike et al., 2018). To the best of the author's knowledge, this study is the first that the 10R strategy has been applied in the LED lamp recycling process and investigated the opportunity to facilitate higher value retention options.

https://doi.org/10.1016/j.spc.2021.07.025

The share of solid-state lighting increased from 5% in 2013 to 46% in 2019 and is predicted to be over 95% in 2030 (Abergel, 2020). Adjusting the demand growth of the lighting services – about 50% by 2030 – electricity consumption would be reduced by around 23% of the business-as-usual-scenario, equivalent to a reduction of 640 TWh of electricity and a saving of 390 Mt of CO_2 emissions (United Nations, 2017). Furthermore, considering the countries that have lagged behind the current market penetration rate, the benefits of using this efficient lighting would be even higher. The lifespan of LED lamps differs widely depending on technology, applications, and usages. In a residential setting, the lamp would be discarded after about 18 years with an operating time of 2.3 hours per day. In contrast, in a non-residential setting, the same light would join the waste stream in about four years, as the operating time is estimated to be 11.2 hours per day (Qiu and Suh, 2019). Unlike an incandescent lamp, which is discarded after failure, the useful life of LED lights ends when the luminous efficacy of an LED lamp declines to less than 70% level (Buchert et al., 2012; Rahman et al., 2019). However, the failure of LED lamps is possible due to insufficient heat dissipation, high temperature, and poor quality electronics. Efficiency improvement may also lead to early retirement, leading to valuable resources in the waste streams (Dzombak et al., 2019).

These factors entail that a substantial amount of waste LED lamps will soon join the electronic waste stream. In 2016, out of 0.7 Mt of waste lamps generated worldwide, about 49,000 tons (7%) of LED lights entered the waste streams. Kumar *et al.* forecast that in Canada, in 2021, about 20% of the waste lamps would be LED lamps (Kumar et al., 2019). Although the share of waste LED lamps in the waste stream is increasing, suitable end-of-life (EoL) management solution is yet to be found. The EoL management is needed because, unlike the preceding lamp technologies, LED lamps contain substantial electronic components, representing about 60 different materials (Reuter and van Schaik, 2015; Zamprogno Rebello et al., 2020).

Furthermore, the design of the material mix does not follow any consistent pattern, which makes recovery of strategic and precious metals difficult (Reuter and van Schaik, 2015). WEEE directive (European Parliament and Council of the European Union, 2012) stipulates that 80% of waste electrical and electronic equipment should be recycled. The challenges are of two folds: many fractions (for example, plastic) do not have dedicated recycling processes, and (ii) existing technology, market pricing, and policy does not explicitly support valuable and strategic material recovery (Qiu and Suh, 2019).

This study intends to critically review the current recycling technology reported in the documented literature from the 10R perspective. UNEP urges following five-step integrated policy approaches for the transition to efficient lighting technologies. One of them is the environmentally sound management of end-of-life (EoL) lighting products. They emphasized the need for a continuous effort to identify the global best practice to minimize any environmental or health impact. A legal framework to ensure sound EoL activities is also reiterated (United Nations, 2017). Many studies highlighted the need to find a recycling solution (Cenci et al., 2020; Rahman et al., 2017). Evaluating the recycling process through the lens of the 10R strategy would help practitioners understand the best possible options for environmentally optimized LED product management. This study aims to review the EoL processes and evaluate against the 10R strategies, formulating the following research question: Do the circular economy value retention objectives guide the current recycling attempt?

In the next section, a literature review on circular economy and 10R strategies are conducted, followed by the method section. The following section presents an overview of the current proposed recycling processes, followed by the results and discussion section. Lastly, an integrated recycling framework is proposed, followed by a concluding section.

2. Literature review

2.1. 10R Strategies: what do they do?

A circular economy seeks to bolster its attempts to preserve values at every stage of the product life cycle and prevent ways to value leakage. CE strategies represent one step forward to operationalize CE at the implementation level. Unsurprisingly, a modest discussion about a diverse range of strategies beginning from 3R frameworks has been offered, as it promises to capture value leakage. Compared to 3R, 10R strategies are most expansive and can pinpoint activities where values are lost. Still, no concrete 10R strategies have been obtained. For example, Reike et al. (2018) added re-mining as an important and, as they claimed, often ignored approach, while subsequent studies seem adherent to Potting et al. (2017), where the lowest hierarchy represents recovery. Rethink is considered one of the vital aspects in Potting et al. (2017), while Reike et al. (2018) did not consider the strategy. Silhoven and Ritola (2015) explained preferences among the different R strategies by considering parameters such as warranty, level of effort required, and performance. The order of reuse, repair, refurbish, and remanufacture has been the same, but the repurpose has been put high after the 'rethink' strategy. The assumption is that the original function is retained, investing fewer inputs than reuse. While repurpose in Potting et al. (2017) are placed down before recycling, as the function is reutilized for different purposes.

In addition, Uçar et al. (2020) have re-organized different R strategies based on their product system and function level. They pointed out that remanufacturing, for example, can have both original, upgraded, and new functions at the product level. The R strategies have also been classified by loop-type (short, medium and long), product type (product, component and material), and function (original, upgraded and new). Moraga et al. (2019) regroup strategies into six, based on the capacity of the strategies. Five of the six strategies represent preservation of function through sharing platform and creating multifunctional products, preservation of product through lifetime extension such as durability, reuse, refurbish and remanufacture, preservation of components through the reuse, recovery and repurposing of parts, conservation of materials through recycling and downcycling and preservation of embodied energy through incineration. The sixth is the reference scenario, which is a state of waste having no preservation strategy.

The discussion of the difference of strategies advances various aspects of strategies. Based on the 10 R framework that Potting et al. (2017) proposed, Morseletto (2020) explores ways to better operationalized CE strategies for more concrete regulatory targets. He seeks to precise in a quantitative term each of the 10 R strategies, pointing synergies among them. The target-oriented CE strategies help decision-makers formulate specific regulatory boundaries, while the producer would measure to what extent the CE strategies have been incorporated in their production system. The 10R strategies have been expanded in Blomsma et al. (2019), proposing a circular strategy scanner. In the first version of the scanner, 'rethink' plays an expansive role at the function and value retention level. Whether the strategy contributes to reducing impacts at the material extraction, manufacturing and logistics, and use level at the function level, is examined. At the value retention level, 'replace' representing a combination of functions or a product or technology having multiple functions, plays a substantial focus over the other value retention options.

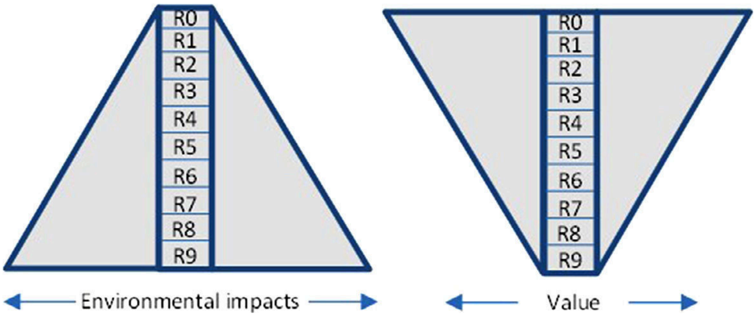


Fig. 1. Relationship of environmental and value with R10 strategies.

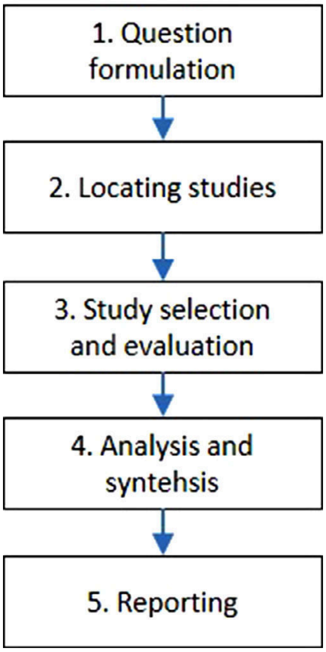


Fig. 2. Methodology of a systematic literature review (adapted from Birkel and Müller, 2020).

2.2. Application of 10 R strategy to evaluate product groups

Very few studies have directly applied R strategies to evaluate EoL management. (Borrello et al., 2017)7 have used a circular economy strategy for the food waste sector without adhering to the 10R strategies. Rodríguez-Antón and Alonso-Almeida (2019) have applied a circular economy strategy in the hospitality sector. They have pointed out that the classic 3 R – reduction (of energy and water consumption, waste generation and single-use plastics), reuse (of energy), and recycling have been more extensively used while redesigning and rethinking strategies play a relatively less vital role. They concluded that the strategies had been applied only perfunctorily, without considering the full potential that a CE strategy can bring. Minunno et al. (2018) have used seven circular economy strategies in the building sector, but not focused on the strict R imperatives, with an order from the reduction of waste from the lean production chain, reuse of waste as byproducts, reuse of components, redesigning using building information modeling and enhancing better tracking capacity through technologies. Gaustad et al. (2018) applied circular economy strategies (reuse, remanufacture and recycle) in mitigating critical material demand. They have pointed out that reuse and remanufacture can improve environmental yield, but recycling plays a crucial role as an alternative supply source. Examples of reuse are plastic grocery bags, sauce jars for drinking, lithium-ion battery repurposed to grid storage. Examples of remanufacturing are plastic resins from HP cartridges. They opined that recycling can be encouraged only after reuse and remanufacture options are applied. Further research, as they pointed out, is necessary to closely study the interaction of the CE strategies, identify difficulties a firm faces to implement strategies, and pinpoint situational and contextual barriers.

Overall, R strategies are not consistently defined or unanimously ranked (Blomsma et al., 2019). Furthermore, R strategies have been applied in only a few areas, while many other areas have still not been investigated. Moreover, there is no standard method to evaluate a product system against the CE strategies.

In this study, we have focused on the application of 10R strategies in the EoL lighting sector. We have adopted 10R strategies proposed by Potting et al. (2017) as it is suitable to apply in LED product system. They are: Recover (R9), Recycle (R8), Repurpose (R7), Remanufacture (R6), Refurbish (R5), Repair (R4), Reuse (R3), Reduce (R2), Rethink (R1), and Refuse (R0). *Recover* refers to incinerating of material and *recycle* to processing for high or low-grade materials. The output of these two R strategies is material. *Repurpose* refers to the use of discarded products or parts for different functions; *remanufacture* refers to the use of parts from a discarded product in a new product for the same function; *refurbish* refers to the upgrading of an old product; *repair* refers to the maintenance of the defective product; *reuse* refers to the use of an old product by a different user. The output of these five R strategies are products or parts and also functions. *Reduce* refers to increasing efficiency during the manufacturing of the product and fewer natural resources; *rethink* refers to making product use more intensive, and *refuse* refers to abandoning products, i.e., they are not required. These three R strategies involve rewinding the manufacturing processes. These ten strategies have been classified into three categories, namely application in materials (R8-R9), lifespan extension of products and parts (R3-R7), and more ingenious product use and manufacturing (R0-R2).

More innovative product use and manufacturing (R0-R2) starts with the design and development of the product – influencing performances of the other (R3-R7) strategies. The design concept is comprehensive, encompassing production processes, logistics systems, consumption patterns, and lifestyles. To realize the (R0-R2) strategy involves re-organizing technological as well as social systems. Designers are critical enablers of these strategies. Design research is has existed for some time, but the target for more quantified improvement is non-existent. Targets for enabling higher circularity (R3-R7) may also be adopted: the percentage of products that can be easily disassembled, repaired, or upgraded; the percentage of products under closed-loop logistics; the percentage of products favoring rare earth elements (REEs) recovery and the percentage of products under Product Service Systems (PSS).

In general, the higher the value retention options, the lower the environmental impacts are, and the greater is the value available

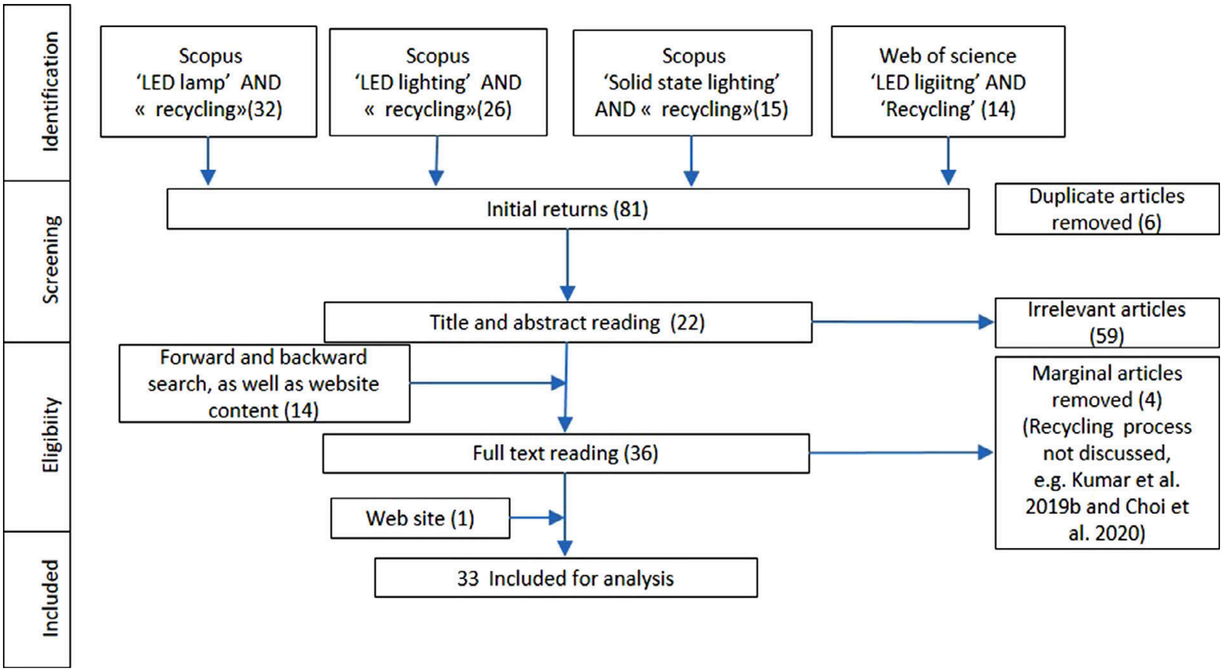


Fig. 3. Study selection diagram.

for further use (Fig. 1). The higher value retention options entail a reduction in natural resources for the production of new materials. The impacts avoided by the lower production of primary materials benefit the environment. In addition, for higher circularity, structural integrity is preserved, whereas it would be destroyed if the lower circularity strategies were applied. Infinite circularity is not always environmentally beneficial, especially when more energy is required for the chemical recycling of highly contaminated plastic (Potting et al., 2017). However, higher-order circularity can lead to unintended consequences through rebound effects, e.g., car-sharing leads to increased car use by people who would not otherwise use a car for travel.

Lower-order circularity (R8-R9) requires technological innovation, while higher-order circularity involves – in addition to technology – socio-institutional change (Potting et al., 2017). For example, packaging-free shopping consists of a reorganization of culture, attitude, and the acceptance of the change. Likewise, a scheduling adaptation is required for the collective use of a washing machine and dryer, which requires manufacturers and designers to make considerable changes. Thus, the implementation of higher-order circularity remains challenging: involving mobilizing society and reframing institutional principles and frameworks. Moreover, lower levels of circularity usually have more rules and regulations (Morseletto, 2020), while higher-order circularity strategies have few or no targets.

Recycling (R8) is the most common strategy aimed at diverting waste from landfills. Recycling is not impact-free and can be either upcycling (if a value equals or increased) or downcycling (if diminished). The varying level of benefits is also associated with open vs. closed-loop recycling. In terms of materials, challenges exist in recycling strategic materials. A CE framework prefers to focus on the strategic metals, for which Europe is dependent on the import from a limited number of exporting countries (Ellen MacArthur Foundation, 2012). However, the recycling rate of those metals is often reported to be very low (about 1%), probably due to technological limits and variations in the methodological calculation of rates (Horta Arduin et al., 2019).

Moreover, it seems that the supply of those metals exceeds the demand in most circumstances, which often results in a low market price for those metals (Zhou et al., 2017). Therefore, it is not economically feasible to recover REEs and other critical raw materials (CRMs) from products due to their low value (Qiu and Suh, 2019). Furthermore, from the environmental perspective, not recovering these metals can harm human health and the environment in the form of landfill leachate (Pourhossein and Mousavi, 2018). In addition, the current focus on mass recycling may encourage downcycling. Therefore, to eliminate or minimize this disincentive, the WEEE directive may add a target for recovering REEs or precious metals.

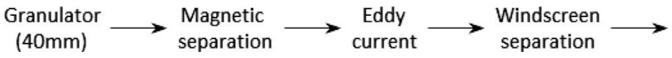
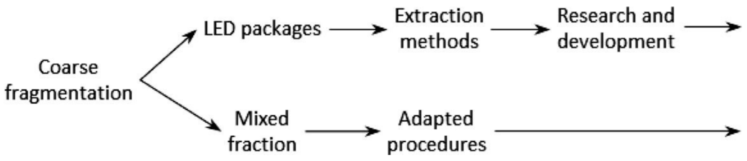
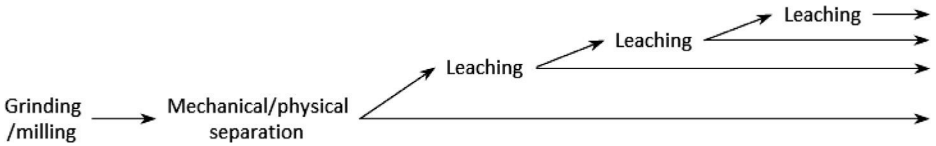
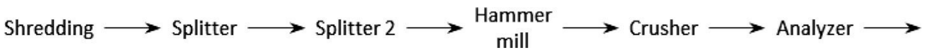
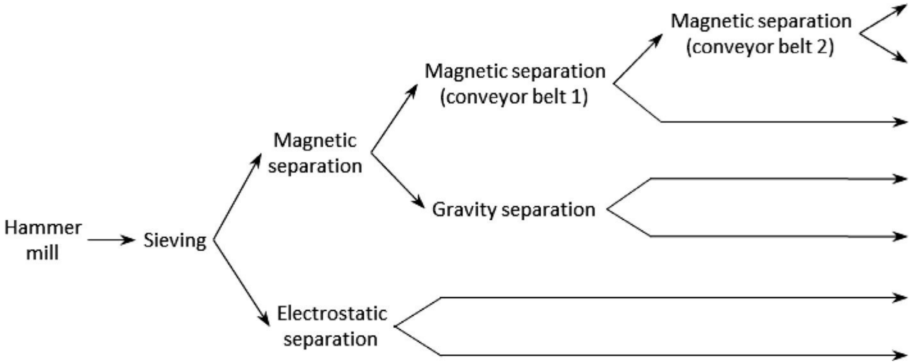
2. Method

The objective of this review is to investigate existing academic studies on the LED lamp recycling process. This paper adopted a systematic literature review (SLR) approach to identify studies, explore the content concerning the theoretical framework, evaluate and analyze data and present the results (Denyer and Tranfield, 2009). In SLR, different steps are needed to be clearly stated and presented so that the study can be replicable (Rousseau et al., 2008). A five-step methodology proposed by Denyer and Tranfield (2009) is followed, which is widely accepted in the review studies (e.g., Birkel and Müller, 2020) (Fig. 2).

First, the *research question* has been formulated based on the initial literature scoping and discussion on the pressing challenge of this new technology. The EoL LED lamp recycling challenge is that the conventional crushing and grinding technology loses about 40% of the valuable materials. The authors collect information from the articles related to one or multiple R strategies, offer analysis of how they are related, present results, and provide future direction.

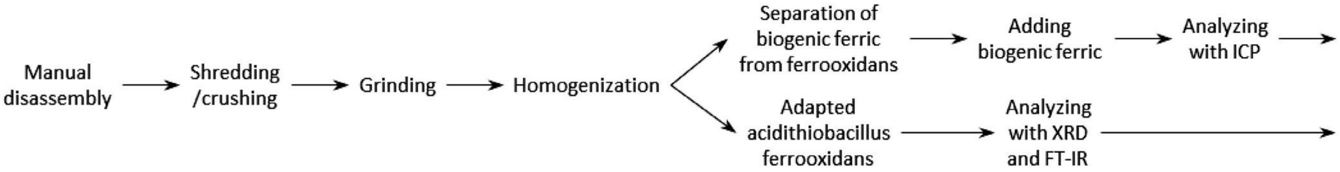
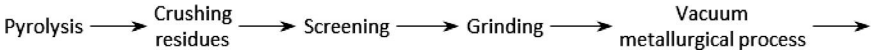
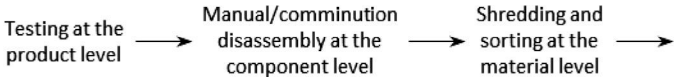
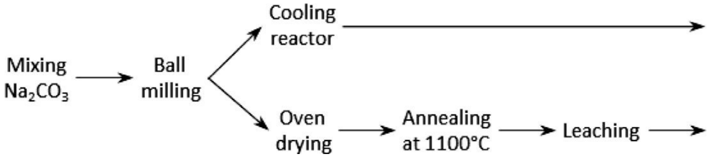
Second, to answer the research question, it is essential to *locate relevant studies*. Therefore, a database-driven search using Scopus and Web of Science have been applied. Scopus has been used as a primary database covering over 20,000 peer-reviewed journals and the Web of Science to ensure any relevant articles are left. The keywords "LED lamp" AND "Recycling" and "LED lighting" AND "recycling" were used to search at Abstract, Title, and Keyword levels, which brought 32 and 26 hits, respectively. No time frame has

Table 1
LED recycling process steps in different studies (summarized form of process lines).

Sample	Processing steps	Output	Reference
Waste LED lamps		**Recyclate**	(Reuter and van Schaik, 2015)
		**Glass Metals Plastics Ceramics Electronic components**	(LED professional, 2016)
		**Arsenic Gallium Indium Plastic and metal**	(Van den Bossche et al., 2019)
		**Fine fractions for metal analysis**	(Kumar et al., 2019)
		**Heat sinks with LEDs PCBs Edison screws Metallic housings Polymeric covers Polymeric housings Capacitors, coils, wires**	(Martins et al., 2020)

(*continued on next page*)

Table 1 (*continued*)

Sample	Processing steps	Output	Reference
Pin type LEDs		**Copper Nickel Gallium**	(Pourhossein and Mousavi, 2019)
LED chips		**Gallium Indium Gold Silver**	(Zhan et al., 2015)
		**Parameter testing**	(Zhou et al., 2019)
Waste LED lamps		**Recyclate**	(Rahman et al., 2019)
LED Chips (dust)		**Indium Gallium**	(Swain et al., 2015)

been chosen, and the type of publications is limited to papers and conference proceedings.

Third, an SLR involves *study selection and evaluation*. The selection criteria of an article include if the study (1) proposes a recycling process, (2) discusses EoL management, or (3) mentions circular economy strategies in the title and abstract. No study has been excluded based on the quality criteria. The additional search with keywords "Solid State Lighting" AND "recycling" (returns 15 articles, but no new article was found) signals the nearly exhaustive list in the database. The Web of Science with keywords "LED lighting" AND "recycling" returns 14 research articles, but only six new papers have been found fresh and relevant after the title and abstract reading. Thus, a total of 22 articles have been selected after the title and abstract reading. Having understood that the number of documents may not be well enough for a robust conclusion, we have adopted a forward and backward search procedure, following Wohlin's (2014) guidelines, adding 14 more pieces (e.g., Lim et al. 2011, 2013). The backward and forward snowballing is justified for a field that is emerging and the keywords used are diverse. After full-text reading, four articles have been removed due to limited discussion on EoL management and Rs (Fig. 3). A related web search included an additional article (e.g., LED professional, 2016). Altogether, 33 articles have been selected for further analysis.

Fourth, an SLR involves data analysis and synthesis. As mentioned above, three criteria have been used for the collection of data in two subsequent phases. Firstly, the studies that extensively discuss a process have been reviewed, focusing on process parameters, the study scope, initial sample, and recovery potentials. Data on the economic and environmental aspects of the studies have also been collected. Secondly, the data related to the different R strategies have been collected. Finally, the data (synthesis and analysis) were grouped, categorized and reviewed by co-authors and external project partners. No disagreement on consistency was raised.

Finally, the result has been presented. First, process-related results have been introduced, summarizing the essential steps of the LED lamp recycling process (supplementary material), followed by the analysis in two stages: preprocessing and post-processing. Nature, challenge, and contribution involved in each of the two stages have been reported. In addition, how R strategies are reflected in the proposed recycling processes have also been presented.

3. Results

3.1. Study by years and country

Research on LED recycling has only gained attention in the last couple of years, which corresponds to the increasing number of LED lamps found in the electronic waste streams (Fig. 4). It is expected that in the coming years, more studies on LED waste lamps will be carried out. So far, only a few countries have participated in LED recycling studies. Except for Iran and Brazil, all the countries represent developed economies and early adopters of the LED technologies. Studies published in the USA are by far the most significant number (8), followed by China, Brazil, and Netherlands (three articles each). Emerging countries such as China and India are still under-represented.

3.2. Analysis of the recycling processes

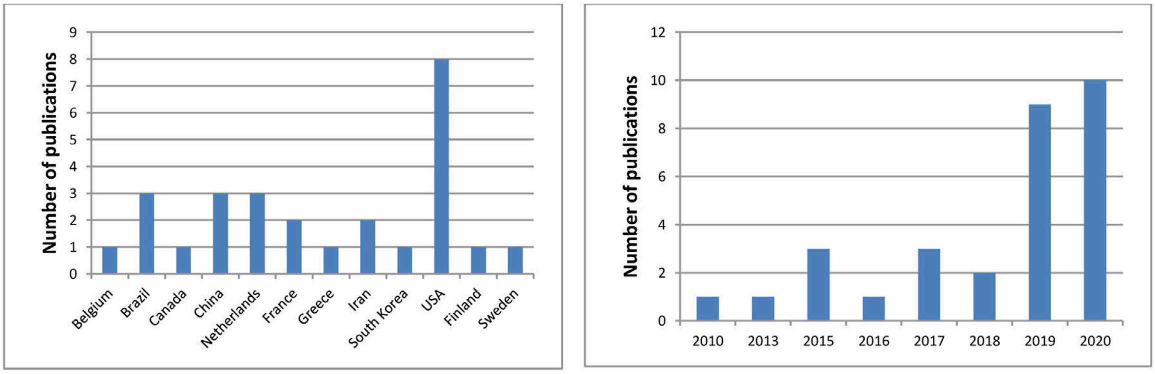
3.2.1. Preprocessing

Table 1 presents recycling stages in the different studies. A detailed description of these stages has been offered in the supplementary file. Recycling processes involve two vital stages. First, preprocessing steps include waste collection from the collection point to the treatment in the recycling facility. Second, the treatment in the recycling facility represents shredding and sorting techniques as mechanical processes. Shredding uses physical force to cut input products into the desired size range. All waste inputs – irrespective of their type – are cut or broken, aiming at better liberation so that purer material fractions can be found after sorting. Standard sorting techniques include gravity sorting, magnetic separation, eddy current separation, and electrostatic separation (Table 1). The sorted materials include ferrous, non-ferrous, plastic fractions as well as electronic components.

The first preprocessing step includes the initial breakdown of the waste LED lamps. Different terms were used in different studies, but their differences are often unknown (Table 2). For example, breakdown of the LED lamps was represented by granulation in Reuter and van Schaik (2015), shredding in Rahman et al. (2019), crushing in Zhou et al. (2019), grinding in Zhan et al. (2015) and ball milling in Zhou et al. (2019). Some studies have applied these steps sequentially. For example, Zhou et al. involved crushing to an initial breakdown and ball milling for further fragmentation. Zhan et al. used crushing for an initial breakdown and then grinding for further fragmentation.

An alternative or complementary approach to shredding/crushing/grinding is comminution (LED professional, 2016). LED professional (2016) mentioned the comminution process, including how it functions. Interestingly, Martins *et al.* applied 'hammer mill' as a comminution process, but no further detail is offered. Comminution allows coarse fragmentation of the waste LED lamps. This method is executed through shock waves in a water medium, which acts on the weakest interfaces of the lamps, leading to a coarse modular fragmentation. The execution can be done in several stages, depending on the level of liberation required. By regulating the pulsed, high voltage (HV), different levels of fragmentation can be obtained. For example, a few HV pulses can make single components disintegrate, while more intense pulses would further break the components into fine particles. The appropriate choice of process parameters is thus crucial to get the desired results. Kumar et al. (2018) compared liberation of eight different LED lamps at 25 and 100 pulses. They found that metals are liberated at a coarser fraction with fewer fines. They also found that increasing pulses liberate more components from coarser fractions. However, they noted that metal casing lamps (3 out of 8 samples) remain unaffected even at 100 pulses. In addition, electricity consumption is very high (157 kWh/t at 100 pulses) than conventional shredding methods. They opine that the comminution can be feasible for the initial weakening stage, and then the conventional technique should be applied for better liberation and recovery.

The application of this technique avoids free mixing of the minor elements in the LED lamps, allowing better sorting results. Martins et al. (2020) also performed sorting on the component-based fractions resulted from hammer mill, slightly different than the comminution. The sorted categories are Edison screw, polymeric cover, polymeric housing, metallic housing, LED module, printed circuit boards, capacitors, coils, and wires, using electrostatic separation, magnetic separation, and gravity separation. The process is innovative because it helps further treatment based on the components, enabling recovery of the relatively purer bulk material from the corresponding component and avoiding unnecessary mixing of the materials across different components. It is noteworthy that only a few components (LED module and electronic components) contain complex multi-material mix, often with minor quantity involved, while other components consist of a few materials (e.g., Edison screw consists of iron and nickel). In addition, precious and REEs can be relatively recovered from the LED module and electronic components by treating them in the refineries. In contrast, mixing components (in shred-



(a) (b)

Fig. 4. Number of publications by country (a) and by year (b).

Table 2
Different terminology representing the initial breakdown.

Process step	Vocabulary used	Reference
Initial small breakdown	Granulation	(Reuter and van Schaik, 2015)
	Crushing	(Zhan et al., 2015; Zhou et al., 2019)
	Grinding	(Zhan et al., 2015)
	Ball milling	(Zhou et al., 2019)
	Shredding	(Rahman et al., 2019)
Comminution	Electrohydraulic fragmentation	(LED professional, 2016)
	Electrohydraulic fragmentation	(Rahman et al., 2019)
	Ball milling	(Martins et al., 2020)
LED parts	LED module	(Cenci et al., 2020)
	Heat sink with LEDs	(Martins et al., 2020)

ding) reduces sorting efficiency and increases the loss of precious metals.

Yet, another alternative step is manual disassembly, which remains an under-studied step in the LED lamp recycling process. For the higher-level circularity (R3-R7), manual disassembly is vital in that it helps produce components that can be reused during remanufacturing. For example, polymer covers or housings, functioning electronic materials can be removed intact for a significant portion of the lamps as an R3-R6 strategy. Dzombak *et al.* conducted manual disassembly of LEDs to identify design challenges that prevent easy access to the different parts of the lamps (Dzombak, 2017). They also develop different indicators to assess the level of difficulty of disassembly and recycling. The overall recycling complexity is found to be relatively low. They found that epoxy resin used to house the drivers often requires a strong force and specific tools and that screw and snap-in connections are often easier to disassemble. The number of parts in waste LEDs increased in 2016 compared to 2013, requiring more effort for disassembly-friendly design. Hendrickson *et al.* identified that 10 to 15 materials, including 2 to 4 different plastics, are used per component (Hendrickson et al., 2010). None of the three disassembled lamps had common parts. They state that products that failed early can be refurbished because the heat sink and other parts are relatively stable except for the conductors. Two essential design changes are suggested: (i) minimizing multiple material types and colors and (ii) labeling the name of the polymer used. They believe that large-scale consumers such as administrations or municipal governments can effectively recycle their devices, as failures are often known and trained technicians can repair or replace defective parts.

The reason for not focusing on manual disassembly is quite apparent but is not discussed in the literature. First of all, in the era of more digitalization, labor-intensive processes are often not realistic and relegated to labor-abundant countries. As the LED lamp recycling process development is mainly employed in developed countries, the labor-intensive process is inappropriate. Secondly, industrial-scale fragmentation techniques – for example, comminution – are being tested to replace manual disassembly. Although the current version of the technology does not perform expectedly, an updated version may solve the current challenges due to product inconsistency. Finally, a more advanced method for component-level recovery could be robotic disassembly, in which different optical and physical parameters can be developed for different lamp designs. Unlike electrohydraulic fragmentation, robotic disassembly could recover more reusable components, including the plastic cover, housing, and other encapsulating materials.

3.2.2. *Extractive metallurgy*

Downstream metallurgy mainly involves selective leaching. Chemical leaching includes extracting a group of selective metals by a chemical reagent, whereas bioleaching avoids chemical reagents. However, the studies are at the laboratory scale and do not explain if the extraction can be applied on an industrial scale. Zhan et al. (2015) investigated the recovery potential of gallium (Ga), indium (In), and gold (Au) from waste LED chips through pyrolysis, physical segregation, and vacuum metallurgical separation (VMS) method. Zhou et al. (2019) investigated the different leaching agents and conditions to identify the best option for high gallium recovery, reaching up to 90.36%. They followed the process from Zhan et al. (2015), using pyrolysis and crushing and ball milling the pyrolysis residues. They compared four leaching agents: hydrochloric acid, oxalic acid, citric acid, DL-malic acid, and four leaching conditions: pulp density, agent concentration, and temperature and particle size. They found that oxalic acid has a highly selective ability due to its easy separation from iron as iron oxalate precipitation. The four conditions that gave the best performance are 10 $g{\bullet}l^{-1}$ pulp density, the oxalic acid concentration of 0.7 $mol{\bullet}l^{-1}$, 90°C temperature, particle size at 48-75 μm, and period 60 min. However, oxalic acid has a very high environmental impact in Liu and Keoleian (2020) study. For the LED module,

Table 3
Recovery potential of the post-processing recovery at the laboratory scale.

Target metal	Process	Recovery potential		Reference
Cu Ni Ga	Bioleaching (*Acidithiobacillus ferrooxidans)*	84% of Cu 96% of Ni 60% of Ga		(Pourhossein and Mousavi, 2018)
Cu Ni Ga	Indirect bioleaching with biogenic ferric	97% of Cu 84% of Ni 83% of Ga		(Pourhossein and Mousavi, 2019)
Ga In Au	Pyrolysis and Vacuum metallurgical separation	**Pure chips** 98.70% of Ga 99.54% of In 98.86% of Au	**Waste LEDs** 93.48% of Ga 95.67% of In 31.59% of Au	(Zhan et al., 2015)
Ga	Pyrolysis and leaching agent	83.42% of Ga		(Zhou et al., 2019)
Ga	Na_2CO_3, ball milling, annealing, and hydrochloric acidic leaching	73.68% of Ga		(Swain et al., 2015)

Zhu et al. (2020) applied different solvents to identify and recycle the content material. They identified that about 70% of the LED module containing plastic polymer can be recycle as the structure remains unchanged after the solvent dissolution. Moreover, the solvent used is regenerated, indicating the process is not environmentally harmful.

To avoid environmental impacts from the chemical agent used, a bioleaching process is suggested. Pourhossein and Mousavi (2018) focused on recovering copper, nickel (Ni), and gallium. They employed a bioleaching method using adapted *acidithiobacillus ferroxidans* to recover metal from electronic waste. The essential aspect of this study is to find a congenial atmosphere for bacterial growth and continue to perform oxidation at the desired rate for maximum recovery. Usually, bacterial growth does not persist in a toxic environment containing highly concentrated heavy metals such as LED waste. However, an adaptation process can help bacteria to perform in a higher concentration. The adaptation method is based on two factors: bacterial cell concentration and the rate of oxidation. The idea is to increase LED powder concentration gradually so that the bacterial community has time to mutate and adapt to a slightly challenging environment. 20 $g \cdot l^{-1}$ of LED powder was the optimum concentration, in which the adaptation process can continue.

Bacterial cells fail to grow and halt the oxidation process at a higher concentration than that (Pourhossein and Mousavi, 2018). A bioleaching method is more environment-friendly, but the management of bacterial sensitivity is challenging. The study does not mention its potential for industrial-scale applications, nor if it could potentially recover other valuable metals, such as gold. The same authors also suggest an updated process next year. They were applied through the production of biogenic ferric from the same *acidithiobacillus ferroxidans* culture (Pourhossein and Mousavi, 2019). The authors claim that this method is the most cost-effective and environmentally friendly for recovering copper, nickel, and gallium. They also mentioned that the process is less time-consuming and more straightforward.

The recovery potentials reported in different studies are only for few selective materials: copper, nickel, gallium, indium, and gold (Table 3). All five studies attempted to recover gallium with a recovery potential ranging from 60% to 98.7%, while copper and nickel recovery is reported in only two studies. Copper recovery potential ranges 84% to 97% and nickel from 84% to 96%. Gold recovery potential is 96.6% in Zhan et al. (2015) from the LED chips. However, it drops significantly (31%) when processed from the waste LED lamps. Indium recovery potential is reported at 99.54%. The bioleaching process jointly recovers three metals: copper, nickel, and gallium, while Zhan *et al.* report gallium, indium, and gold recovery altogether. The bioleaching process recovered 83% of gallium and claimed to be environmentally friendly as they used an organic leaching agent (Table 3).

Different parameters are identified in the literature (Table 4). It seems that the leaching step performs well in a particular atmosphere with temperature, pressure, paste density, particle size, and leaching agent. Zhou et al. (2019) compare the optimal function of different leaching agents, the concentration at which the agent functions optimal, the density and particle size of the sample, and the temperature and pressure of the reacting atmosphere. Oxalic acid at a concentration of 0.7 M with pulp density of 10 $g{\bullet}l^{-1}$ and particle size, 48-150 µm, with a temperature of 363 K and a pressure of 0.1-1.0 Pa, gallium recovery is optimal. The recyclability parameters include the value of the resources potentially recoverable with the available technology and the cost of recycling. The resource index and technology index are identified as essential parameters for determining the economic feasibility of the recycling process. The replacement cycle represents the lengths of time a particular innovation functions before becoming obsolete and eventually replaced by a more efficient innovation. Dzombak et al. (2019) and Liu and Keoleian (2020) addressed the effect of replacement on waste generation, with the possibility of early obsolescence of the whole product or a part. Reuter and Van Schaik (2015) discuss input characteristics as an important parameter that defines the recovery potential at the end. In other words, a product containing parts that release easily can potentially release more reusable components with a higher value (Dzombak, 2017). Several articles also indicate that metals' concentration in LED lamps is higher than their ores, indicating more excellent recyclability.

3.3. Sustainability assessment: environmental and economic

Several *environmental* life cycle assessments have been conducted for the whole life cycle of the LED lamps from cradle to cradle perspective, in which EoL data inventory and the impact assessment have been hypothetically generated. These studies showed that the EoL stage involves less than 1% of the overall lifecycle impact (Principi and Fioretti, 2014). The findings of this nature may undermine the need to employ rigorous effort required to exclusively focus on EoL impact assessment (Rahman et al., 2017, 2019). However, Lim *et al.* investigated toxicity potentials of the CFL, LED, and incandescent bulb and concluded that LED bulbs have 2-3 times higher impacts in terms of resource depletion and toxicity potentials than incandescent bulbs due to their high content of aluminum, copper, gold, lead, silver and zinc (Lim et al., 2012). This assessment provides insight into the potential harm the LED lamp may cause if the EoL stage is not optimally managed.

The recycling process itself can be environmentally problematic, depending on the choice of the solvent used. Liu and Keoleian (2020) conducted a lifecycle assessment of an LED light and a compact fluorescent lamp (CFL) for one kilogram of gallium recovery. They found that gallium recovery from LED lamps causes more environmental impacts than its recovery from natural ore processing due to oxalic acid in the leaching process, which dominates almost all environmental categories. This finding is interesting for the industrial stakeholders to be careful about spe-

Table 4
Identification of the parameters necessary for the various sub-processes.

Parameter	Value	Processing scope	Source
Temperature	1373 K (Pyrolysis) /363 K (Leaching)	Leaching	(Zhan et al., 2015; Zhou et al., 2019)
Pressure	0.01-0.1 Pa	Leaching	(Zhou et al., 2019)
Concentration of Leaching agent	0.7M	Leaching	(Zhou et al., 2019)
Leaching agent	HCl, Aqua regia, Oxalic acid	Leaching	(Zhou et al., 2019)
Bioleaching agent	-	Leaching	(Martins et al., 2020)
Recyclate quality	-	Shredding and sorting	(Reuter and van Schaik, 2015)
Economic feasibility	-	Recyclability	(Cenci et al., 2020)
Resource index	-	Recyclability	(Qiu and Suh, 2019) (Fang et al., 2018)
Concentration of metals	-	Recyclability	(Cenci et al., 2020; Zamprogno Rebello et al., 2020)
Input characteristics	-	Recyclability	(Reuter and van Schaik, 2015)
Technology availability	-	Recyclability	(Reuter and van Schaik, 2015)
Replacement cycle	-	Early retirement	(Dzombak et al., 2019)
Pulp density	10 g•l^{-1}	Leaching	(Zhou et al., 2019)
Particle size	48-150µm	Leaching	(Zhou et al., 2019)
Modularity		Disassembly	(Dzombak, 2017)

Table 5
Different economic parameters identified in the LED recycling literature.

Economic parameters	Quantity	Unit	Source
Capacity	0.06	ton per hour	(Martins et al., 2020)
Capacity	1500	ton per year	(Qiu and Suh, 2019)
Working days	250	per year	(Martins et al., 2020)
Industry service life	10	years	(Martins et al., 2020)
Transport costs to recycling facility	300	USD per ton	(Martins et al., 2020)
Electricity	0.11	USD per kWh	(Martins et al., 2020)
Cost of equipment	117,514	USD	(Martins et al., 2020)
Phosphor powder purchasing cost	1000	USD per ton	(Qiu and Suh, 2019)
Labor costs	1	USD per hour	(Martins et al., 2020)

cific leaching techniques. The bioleaching process is promising because it avoids the use of chemicals (*i.e.*, oxalic acid). However, an assessment of the claimed environmental benefits is yet to be offered.

Another assessment at the end-of-use level has been conducted, highlighting the user dilemma of replacing the old lamps. Based on the case of street lighting and using the Markov decision process and lifecycle assessment, Dzombak et al. (2020) found that cost and environmentally optimal decisions are not aligned. The cost-optimal decision strategy supports the use of the product as long as possible due to the amortization of the initial cost. However, environmentally optimal decisions encourage frequent replacement of new technologies by reusing obsolete ones. Based on these studies, it can be said that considerable uncertainties exist in the EoL management of the LED lamps in terms of when to discard, when to reuse, whether to recycle and how to recycle.

Economic assessment has not been systematically conducted at the process level. However, some preliminary estimations have been offered in several studies. Martins et al. (2020) argued that LED lamp recycling could be cost-effective through mechanical recycling focused on component-level shredding and segregation. They conclude from the Brazilian context that the profit margin is more than 600 USD per ton (Table 5). Rahman et al. (2019) provided a cost comparison between product, component, and material recovery. Product level recovery would be cost-effective (about 4,000 USD per ton), assuming that the reusable lamp can be sold at 1 USD per lamp. For material level recovery, the profit is about 100 USD per ton, while for the component level, the profitability of manual disassembly is about -4,000 USD per ton. The reasons for this negative profitability are: (i) the component's price is estimated to be the same as the yield of the shredding materials, and (ii) the labor cost is about 60 USD per day. The detailed economic parameters and their corresponding value have been collected in Table 6.

The value recovery potential from the waste LED lamps has also been estimated in several studies, suggesting that the economic feasibility of the waste LED lamps recycling holds promise if precious metals such as gold could be recovered. Kumar et al. (2019) evaluate the economic potential based on the metal content in the waste LED lamps based on a 100% collection and recycling scenario. The results showed that more than 10 million Canadian dollars could potentially be saved with gold and aluminum contributions (83% and 12%). They pointed out that no study to date realistically evaluated the collection and recycling rate of used LED lamps. Cenci et al. (2020) linked component and material content to material prices. They identified potentially essential components and materials in the LED lamp and tubes, displayed in a Sankey diagram. They found that with a recycling rate of 28% for lamps and 18.96% for tubes, the total economic value of the components is 2,274 and 2,062 USD per ton, respectively, representing a recovery value of about 53% each. PCB has the highest economic value for LED lamps (1,276 USD) and LED modules (1,370) for tubes. On the material side, gold has the highest value for both lamps and tubes at 1,800 USD. Cenci et al. (2020) and Martins et al. (2020) argue that early segregation favors economic feasibility.

Economic assessment for recovering REEs has also been investigated. Qiu and Suh (2019) conducted a study on the economic feasibility of recovering REEs from the LED lamp recycling process. They conclude that supply rate or plant capacity is an important factor that reduces the overall cost of the recycling process (Qiu and Suh, 2019). They found that for a recycling capacity of 100 tons per year, 800 tons per year, and 1500 tons per year, the REEs price range must be multiplied by 6.3, 2.8, and 2.2, respectively, to break even. They assumed that the scale factor is -0.39. Using dynamic material flow analysis, they showed that with a high LED penetration scenario, 85% of the rare earth oxide (REO) supply would be shared by EoL LED lighting, while in a low LED penetration scenario, the fluorescent lamp would continue to be the dominant supplier (90%).

The decisive factor for the economic feasibility of the LED lamp recycling is the labor price: 1 USD per hour for Brazil

Table 6
LED recycling literature representing Rs strategies.

Study objective	Year	Rs discussed?	Smart manufacturing and use			Life extension of products and parts					Useful application of materials		References
			R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	
Benefits of recycling	2020	No											(Grigoropoulos et al., 2020)
Characterization	2020	No											(Choi et al., 2020)
Characterization	2020	No											(Cenci et al., 2020)
Characterization	2020	No											(Zamprogno Rebello et al., 2020)
Characterization	2019	No											(Kumar et al., 2019)
Criticality and recyclability	2018	No											(Fang et al., 2018)
End of life design	2010	Yes		☐	☐		☐	☐	☐	☐	☐		(Hendrickson et al., 2010)
End of life design	2017	Yes		☐					☐		☐		(Dzombak, 2017)
End of life design	2017	No											(Rahman et al., 2017)
Impact estimation	2013	Yes				☐	☐	☐	☐		☐		(Lim et al., 2011)
LCA	2020	Yes				☐	☐	☐	☐		☐		(Liu and Keoleian, 2020)
LCA technology transition	2020	No											(Dillon et al., 2020)
Rapid technology cycle	2019	Yes				☐	☐	☐					(Dzombak et al., 2019)
Rapid technology cycle	2020	Yes		☐		☐	☐	☐			☐		(Dzombak et al., 2020)
Recycling	2020	Yes									☐		(Martins et al., 2020)
Recycling	2019	Yes									☐		(Qiu and Suh, 2019)
Recycling	2015	Yes									☐		(Reuter and van Schaik, 2015)
Recycling	2019	Yes		☐		☐	☐	☐	☐		☐		(Rahman et al., 2019)
Selective recovery	2018	No											(Pourhossein and Mousavi, 2018)
Selective recovery	2019	Yes									☐		(Van den Bossche et al., 2019)
Selective recovery	2019	Yes									☐		(Zhou et al., 2019)
selective recovery	2019	Yes									☐		(Hämmer et al., 2018)
Selective recovery	2020	Yes									☐		(Zhu et al., 2020)
Selective recovery bioleaching	2019	Yes									☐		(Pourhossein and Mousavi, 2019)

(Martins et al., 2020) versus 65 € per day in France (Rahman et al., 2019). However, the extended producer responsibility provides a premium for the European nation that makes the recycling activity favorable for their territory. Therefore, Rahman et al. (2019) estimated very high profitability for the product level reuse. However, so far, that market is non-existent.

Fang et al. (2018)pointed out that despite the potential option for recovering gallium, indium, and REEs from the end-of-life LEDs, existing metallurgical recycling methods have focused on a few individual metals with low recycling rates and caused high environmental consequences. Effective looping of LED waste lamps is still a long way off. A thorough understanding of the nature of the technology situation is crucial. Many factors that influence economic and technology viability are still not adequately studied. The typical steps to recycled LEDs – collection, dismantling, pretreatment and recovery – are not thoroughly studied from an economic perspective, considering logistics, material prices, and potential revenue generated. The technological availability for a suitable pre-treatment and basic metallurgy must also be evaluated against the economic profitability. Otherwise, innovation would be delayed or abandoned (Feng et al., 2018). LED lamp recycling is at this crossroads where an efficient recycling process may not be economically lucrative, while the economically attractive aspect may not be technologically feasible.

4. Discussion

From the above discussion on the recycling processes adopted in the EoL LED waste streams at the laboratory level, it is evident that the intent behind the preliminary attempt was, to some extent, inspired by the circular economy principles.

Table 6 shows that lower-level circularity (R8) remains the dominant approach for the proposed recycling. The need for strategic materials inspired selective leaching for material recovery. Under the lower level circularity, some innovative approaches have been proposed for better resource efficiency. For example, LED professional (2016) suggested a coarse fragmentation approach to concentrate and segregate the electronic parts, heatsink, and LEDs. They assert that LEDs are like contaminants for other fractions and hence need to be separated. At the same time, they can be effectively processed for strategic and critical materials.

Few studies have attempted to highlight the medium and high-level circularity processes. Rahman *et al.* applied CE value retention options and explored different scenarios from the cost and benefit perspective, identifying challenges for higher-level circularity (Rahman et al., 2019). Martins *et al.* performed component-level fragmentation, instead of shredding, for material recovery, with an industry scale experimentation for mid-level (R4-R5) circularity (Martins et al., 2020). As R1, design challenges were highlighted, and modifications were outlined by Hendrickson et al. (2010) and Dzombak (2017). Dzombak *et al.* propose the Light As A Service (LaaS) model (Dzombak et al., 2019). The shift to the LaaS model – retaining producer ownership – tracks obsolete products in terms of failure and upgradeability and, at the same time, informs design that promotes reuse. On the other hand, consumers would benefit from updated services at comparable service costs. Several companies have already started to try this business model (Dzombak et al., 2020).

4.1. Connecting R strategies

R0: The reviewed study provides no information regarding the R0 strategy. However, R0 may occur if LED lamps are incorporated with digitalized technologies in the future. For example, Li-Fi in LED lamps may become redundant to the internet connection's modem (Energyfocus.com, 2020). The additional function would add a new device in the lamps, making it more complex for the EoL management.

R1: Future development of LED lamps may be more human-centric by applying color tuned technologies, dimming capabilities, and occupancy sensing technologies, thus carrying out multiple functions. The intensive and pragmatic use of lighting leads to reduced energy consumption through better alignment with other heating (and cooling) devices in households (Energyfocus.com, 2020).

R2: Reduce involves using less material in manufacturing. Hendrickson et al. (2010) suggest that we should try to minimize the number of materials and label them to use further (or no use). The precise identification enables the R2 strategy by reducing the material consumption by ensuring their better use during the design and manufacturing level. This modification also helps to improve repair, remanufacture, and refurbish strategies- an essential synergy in the CE.

R3: Reuse at the product level has been examined in Rahman et al. (2019). They identified, in the waste stream, a good number of intact and functioning old lamps. Further use of these lamps can be possible upon inspection, standardization, and marketing. However, the secondary market pathways are unknown and pose grand challenges for CE implementation. The lighting consumers are in a dilemma: whether to keep using lighting till the end of its useful life or to throw it early. The former gives them an economic advantage (avoid extra money for new lamp purchase), but the latter gives them an environmental advantage (consuming less electricity and becoming more efficient). However, this mismatch between environmentally optimal and economically optimal use provides more reuse, refurbish, and remanufacturing opportunity if a new business model can be innovated, such as LaaS. LaaS model – Lighting as a service – is proposed by Dzombak et al. (2019), which works like PSS and may be helpful to realize R4/5 strategies.

R4/R5: Repair and refurbish depend on scale, availability of spare parts, technical servicing opportunity. This strategy also depends on failure prediction, identification, and replacement process. For a municipality, a repair can be a good option; through a contract agreement in the form of LaaS with the manufacturers. To realize this, the information related to the product life cycle needs to be available to a dedicated entity to model failure, make decisions to upgrade, replace components, and install for further use at any point on or before EoL.

R6: reusing used parts in the new product is rarely practiced and not customer friendly. Whether a consumer would accept such a product has not been surveyed systematically, to the best of knowledge. Hands-on experience in disassembling aluminum housing-based lamps shows that the entire housing structure can be reused by putting LED chips and electronics in them. The problem is that the housing structure would not be new, and the remaining useful life span is unknown. It is safe to assume that the housing has two-three times more durable than the electronic components. However, the economics for manual disassembly would not allow such operations in the developed world.

The difficulty in R6 lies around social,market, culture, and communication factors. More communication among the user and manufacturer and the exchange of crucial information would help overcome challenges. Also, the development of a successful business model is crucial for the introduction of the secondary market. Cultural orientation towards remanufactured products may require the deployment of effort, resources, and time.

R7: Repurpose is sometimes possible. The low-intensity lamp can be used where applicable, for example, in agriculture or other sectors where dimming lights work fine. However, the supply of such second-hand lamps is uncertain and depends on the rate of early retirement, which depends on the rate of efficiency gain in future products. In addition, it is crucial to identify similar other sectors for a constant demand and a successful business model. Many other intermediate stages are also involved in the supply chain.

R8: Recyle strategy worked fine for the preceding technologies such as CFL lamps. However, for LEDs, obtaining a recovery rate at 80% is difficult as shredding liberates many elements that reduce sorting efficiency and, thereby, the quality of the fractions recovered. Therefore, R8 is realized in the form of selective leaching and the effort for resource efficiency. Reuter and van Schaik (2015) suggested ten design rules for resource efficiency while other suggested component level segregation as discussed above.

Given the technology scenario, some inefficiency and landfilling cannot be avoided. Successful application of early segregation requires the development of related technologies and favorable design modification for a better EoL strategy. Both the process – development of recycling technology and design improvement – should advance simultaneously.

R9: Recover strategy may be required at the plastic level. It seems that recycling some plastics cannot be economically viable to be incinerated for energy recovery. The characterization process is advancing, allowing identification of the type of plastic used in the LED lamps.

4.2. Integrated management framework

Although R8 is the dominant strategy, other strategies can be applied to some extent where possible. In particular, product and component level recovery (R3-R7) has not emerged as a suitable alternative to the recovery process.

Fig. 5 shows an integrated recycling process for LED lamps from a circular economy perspective, starting from the collection activity. It determines the recovery rate at the end. However, studies on the challenges of the collection are lacking. For example, LED lamps are mixed with other collection boxes due to a lack of knowledge and awareness among consumers. In addition, many lamps may not return to the collection boxes due to the small size of the products and consumer behavior as there is no monetary or economic motivation.

Transport may cause a significant impact on the overall LED lamp recycling process, depending on the distance between the collection location and the recycling facility. Therefore, further studies need to be conducted to estimate the transportation impact.

Recovery can be planned at the preprocessing, product, component, and material levels. Reuse at the product level is quite relevant, particularly for the rapid innovation cycle, which leads to immature obsolescence of the still valuable lamps (Dzombak et al., 2019; Rahman et al., 2019). Dzombak *et al.* mentioned that over 60% of costs come from lighting at the municipal level, so continuous efficiency improvement can motivate wholesale replacement of the current system. The strategies (R3-R7) can fit well. Legal and social issues regarding this type of business and enterprise also need to be explored. Rahman *et al.* estimate that more than 50% of waste lamps still function and may be economically feasible (Rahman et al., 2019). However, a product testing and upgrading system need to be put in place, and it may require further investigation to see if such a system is viable in advanced western countries.

The R8 material recovery strategy can be applied to LED lamps only when higher-order strategies are not applicable. For example, lamps that are difficult to access due to epoxy resin can be classified for the R8 strategy. The relationship between material level recovery and the post-processing requirements has not been studied sufficiently. It is not clear from the literature which type of recyclate can be more beneficial for the efficient recovery of pre-

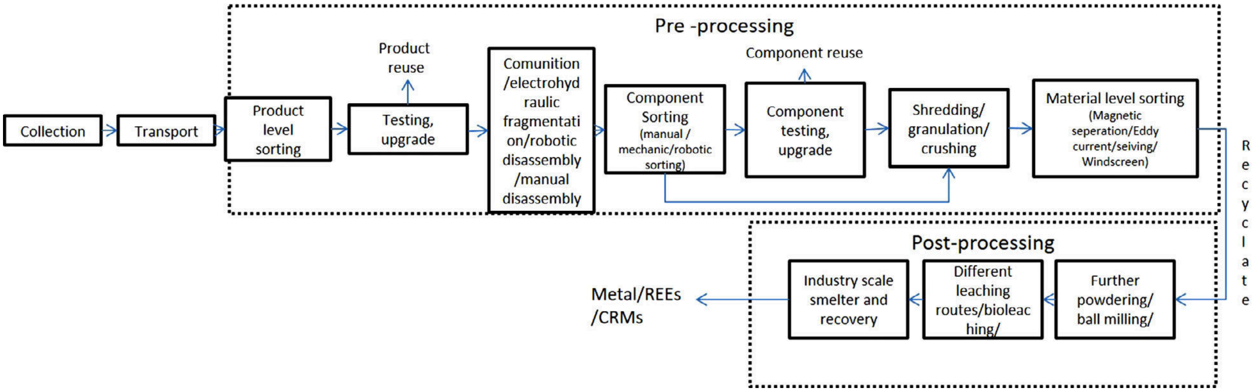


Fig. 5. A schematic diagram of the proposed LED lamp recycling based on the integration of the approaches identified in the reviewed literature.

Table 7
Ten rules for better resource efficiency, adapted from Reuter and van Schaik (2015).

	Rules for DfR	Specific action
1	Oversimplification focusing on general recycling rules would not produce the intended goal of resource efficiency (RE)	Process related innovation
2	Requires model and simulation-based quantification	Estimation tool development
3	Design data should be available and compatible	Compatible Technology development
4	Appropriate technology infrastructure and relevant tools	-
5	Linking design tools with recycling process simulation for designers to be informed about the accurate picture of metal and material recycling	Designer knowledge development on recycling
6	Identify and minimize the use of materials that contaminate the recycling process	Problematic material definition
7	Identify and minimize the use of components that make recycling difficult for combined and applied materials	Problematic component definition
8	Design important; parts to be readily separable	Modular and separable components structure
9	Labeling based on product or component recovery	-
10	Designed for easy liberation of materials	-

cious metals and REEs. In addition, if the laboratory scale leaching can be adapted to the industrial scale. Reuter and Van Schaik have presented several smelting routes, providing the example of a company in Japan (Reuter and van Schaik, 2015). They successfully process four smelting routes – copper, lead, zinc, and nickel – using a mix of hydro- and pyrometallurgical processes. They reported that REEs remain highly stable oxides and are most often found in the ferrous fraction that ends up in the slag. If PCBs and LED chips can be directed to Cu processing routes, the possibility of recovering precious metals is high. They also pointed out that additional granulation can release more precious metals, but with some limitations: the potting material may increase the viscosity of slag and cause additional losses. In addition, the additional dust may increase emissions leading to environmental consequences that need to be assessed. Thus, the post-processing steps marching from laboratory scale to industrial scale involves challenges, which need to identify and address sooner.

Reuter and Van Schaik propose ten design for recycling (DfR) rules for improved resource efficiency (Table 7) (Reuter and van Schaik, 2015). These rules require specific actions from stakeholders such as designers to increase clarity and transparency and better communication to share knowledge about recycling behavior. In addition, some quantification tools are required to develop informed expectations about the rate and quality of recycling.

4.3. *Sustainability implication*

In this study, we have adopted a CE strategy to assess LED lamp recycling and implicitly support the positive sustainability of the higher R strategies. Lee et al. (2021) state that CE and sustainability exhibit trade-off relations.

Sustainability depends on the type of material recovery targeted. For example, if recovery of REEs is targeted, sustainability benefits – environmental and economic - are uncertain, depending on the recycling treatment (e.g., chemical or bio-based) and scale. In addition, colossal value loss occurs if precious metals are lost during treatment, implicating resource efficiency. Furthermore, EoL management must minimize the hazardous material in waste LED lamps before landfilling.

Achieving sustainability is complicated in LED lamps as environmental impacts are primarily in the use phase. LED technology is evolving, which means that early replacement is sometimes economically and aesthetically attractive to users as the following product would be more energy efficient. However, the practice is not sustainable, generating more waste underutilizing valuable resources. Consequently, systematic sustainability assessment is a prerequisite to confirm positive aspects of adopting higher R strategies.

This study would benefit CE as an application to a specific product, illuminating various value retention options. While LED lamp recycling generates less than 1% of life cycle environmental benefit, a comprehensive option other than the R8 would encourage practitioners to identify alternatives, allowing more valuable resources and reducing landfills. Target-oriented regulation, cultural acceptance, and treatment approach (early segregation/ coarse fragmentation/shredding) are critical to achieving sustainability.

5. Conclusions

This paper presents the current LED lamp recycling processes attempted at the laboratory level and evaluated against the 10R strategy under the circular economy framework. It is found that the lower order circularity, namely R8, is the dominant intent behind the laboratory attempt, focusing on selective strategic metals (Ga, In, Au, etc.) recovery and improving resource efficiency. The finding suggests that multiple R strategies should be applied stepwise. R0-R2 is less practiced now, but these strategies can be adapted for a more efficient EoL treatment as the technologies develop. R3-R6 can be applied at the product, component, and functional level, followed by the R8-R9 strategy. The major challenge in the R3-R6 is the introduction of a business model requiring a dedicated entity (e.g., manufacturing firms or collective agencies) that has access to the failure, use, repair, and replacement information. The type of disassembly is crucial for higher R strategies. Developing countries may conduct manual disassembly economically and environmentally, but health and safety hazards would be an issue. The developed country requires technological breakthroughs. Some effort is underway with limited success due to inconsistent product making and content. Theoretically, the rethink strategy should play a crucial role in optimizing economic, environmental, legal, and technological factors.

The implementation of both the higher and lower R strategies has challenges. For example, life extension strategies are impractical by market, culture, and business constraints, while material recovery strategies are inefficient for lamp characteristics and technological constraints. Planning for R8 without considering the other higher strategies would be inefficient. The current effort for selective leaching may help recover strategic metals but is challenged by inadequate input, low market price, and regulation. This study finds that practitioners choose to remain in lower R strategies or break barriers for higher R strategies. Decision-makers may help in formulating appropriate regulatory initiatives through well-defined targets and incentives.

The study contributes to the existing body of CE strategy by applying it to a product group. By choosing the 10R strategy, this study also demonstrates that a more nuanced strategy can significantly contribute to achieve higher circularity The rethink strategy should encompass design, manufacturing, and impact optimization; all are highly relevant in LED lamp management. Furthermore, lower CE strategies in modern products such as LED lamps are inefficient, requiring more robust resource efficiency methods. Further research may investigate the regulatory implications and cultural orientation towards a secondary product.

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.

Acknowledgments

This research was funded by EIT RawMaterials as part of the project "REDLED: Recycling EnD-of-life LED" with the project number 18039.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.07.025.

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