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Responding to the potential environmental impact to extend battery life: Preliminary study of informal actors' readiness

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ABSTRACT

The increasing number of electric motorcycles in Indonesia has created new challenges related to battery waste management, potentially impacting human health, the environment, and resource scarcity. This study aims to assess the potential life cycle impacts of a 1.0 kWh electric motorcycle battery product system under repair treatment for two widely used battery types: NMC and LFP. The study used a Life Cycle Assessment (LCA) method with gate-to-gate assessment. The assessment results for both battery types with repair treatment had the greatest impact on the midpoint of freshwater eutrophication. Based on the normalized results of the five impact categories assessed, the repair treatment on LFP type batteries showed better environmental performance than the NMC type. The balancing process was found to have the greatest environmental impact for both battery types. This study confirms that recycling management by informal actors is a significant solution. The repair treatment solution contributes to providing benefits in extending the battery life cycle and does not have the potential for significant environmental impacts.

1. INTRODUCTION

The enactment of Presidential Regulation No. 55 of 2019 shows the development of increasing sales of electric motorcycles in Indonesia. Although this increase has not been able to meet the target of the Indonesian Government's plan of 8.4 million units by 2030. In 2020, electric motorbikes in Indonesia were recorded at 1,947 units, but in 2022, the number of sales increased to 25,782 units, an increase of around 13 times [1]. At Jan, 2024, data from the Ministry of Transportation showed that the number of issuances of type test registration certificates (SRUT) for electric motorbikes was 99,594 units [2]. The increase continued until 2024, reaching 160,000 units [3].

The 81% increase in electric motorcycle sales between 2020 and 2024 significantly supports the Indonesian government's program and global efforts to reduce greenhouse gas emissions and protect the environment. However, these benefits have quite serious impacts related to the battery waste of electric motorbikes [4]. This battery waste has an impact on human health and the sustainability of the environmental ecosystem.

The serious impact of this battery is due to the content or material of the electric motorcycle battery including hazardous and toxic materials. This battery contains various metal contents such as cobalt (Co), copper (Cu), nickel (Ni), and lead (Pb) which are at risk of endangering health and polluting the environment around the disposal site. T amount of battery waste entering the final disposal site has not shown a specific amount. However, considering that batteries have a limited life cycle, the potential for a massive increase in battery waste will occur, starting in 2026.

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Several environmental observers have proposed solutions related to the management and handling of this battery waste. First, waste management recycling is needed. Second, further research is needed to develop more environmentally friendly battery technology. Third, there needs to be strict regulations regarding waste management by producers and users. Fourth, education is needed for the public regarding the negative impacts of waste and the importance of active community participation. Without strict regulations regarding the management of used batteries, Indonesia is threatened with facing piles of hazardous and toxic materials waste in landfills. Batteries are prone to catching fire and exploding, so they have the potential to cause problems if disposed of in a final disposal site [5].

Currently, Indonesia does not have a waste management company [6]. but the government is reviewing an Indonesian company that will process waste to create a circular economy. The circular economy is closely related to the supply chain because it encourages the transformation from a linear "take-make-dispose" model [7], [8], [9], [10] to a closed cycle that reuses materials and products to reduce waste and increase resource efficiency. The principle of the circular economy is a supply chain that can integrate reverse logistics, recycling, and remanufacturing, thus creating a more sustainable and resilient system.

In Switzerland, the government regulates policies for consumers to return batteries to manufacturers, sellers, or battery collection facilities that have been provided [11]. In the European Union, as stated in the extended producer responsibility (EPR) regulation, manufacturers are required to ensure that the batteries they will market will be recycled properly and prepare a take-back system at no additional cost. Similarly, in China based on the Regulation on Recycling and Reuse of Traction Batteries, manufacturers or importers must be responsible for the collection, sorting, storage and transportation of waste batteries.

Some previous studies state that the treatments that can be carried out are remanufacturing/refurbishment, reuse and repair [7], [8], [9], [10], [12], [13]. According to Slattery *et al*. [12] Kurdve *et al*. [14] and, Shokohyar *et al*. [15], the initial treatment required when an electric vehicle battery is declared to be unusable as waste is repair. Repair treatment is defined as a minor action without charging consumers and can be reused as a motor drive battery [15], [16].

Kurdve *et al*. [14] stated that remanufacturing, reuse and repair treatments will be very appropriate execute by OEMs which do provide more standard quality, but in the future this kind of system will limit consumer mobility and be less efficient. The involvement of actors outside the OEM will provide flexibility in determining the use of used components. In the case of Indonesia, the involvement of informal actors (workshops) can provide OEMs with the opportunity to focus on pursuing government targets.

Informal actors are individuals or groups with established but "unofficial" businesses outside of OEMs [17], [18]. Informal actors in the electric motorcycle battery supply chain are businesses that generate higher revenues from value-added activities such as repair, refurbishment, specialized dismantling, and the aggregation of valuable fractions. They are often unregistered, struggle to register their businesses, operate outside legal control, small-scale, labor-intensive, low-tech processing, and evade tax payments [19], [20].

Batteries as motor drive batteries have a certain life cycle. Several literatures state that battery technology is stated as a more environmentally friendly technology in the usage phase [21], [22], [23]. In order for the battery's usefulness to be long, several literatures propose several treatments that can be carried out so that the battery's life cycle is long. Several treatments that can be carried out are carried out to prepare the battery to enter its second life cycle. The question is whether it is true that the treatment to extend the life cycle does not have the potential to have an impact on the environment.

To assess the potential environmental impact of the treatment phase, researchers chose to use life cycle assessment (LCA). LCA is a proven environmental impact assessment method and is still widely believed to be effective [24]. The LCA method can perform measurements with a scope that can be adjusted to the needs of researchers. The database used is a transparent database that can be accessed by anyone and anywhere. To maintain the validity of the active LCA database to conduct research related to characteristic factor parameters. With standardized and open data, it will maintain the sustainability of the reliability of the method in general.

The main contributions of this study are described as follows:

1) This study is an initial study to see the readiness of informal actors as part of the electric motorcycle battery supply chain, as a form of response to the environmental impact of electric motorcycle batteries that have a limited lifespan.
2) This study produces the potential environmental impact of one of the simplest battery waste recycling treatments, namely repair treatment. This treatment is a very potential treatment that can be carried out by informal actors.
3) This study measures the potential environmental impact of two types of batteries that are most often chosen by several electric motorcycle manufacturers in Indonesia
4) This article provides insight into the potential environmental impact of efforts to extend the battery life cycle in the repair treatment that is

very possible for informal actors

There are many and large positive impacts provided by battery technology, but it is undeniable that it also has a negative impact when the battery is no longer able to be used as a motor drive battery. Management of battery waste is needed so that its life span becomes longer and more useful. Some solutions to extend the life of the battery are repair, remanufacture, refurbishment, and reuse. Technologically, repair treatment is considered a simple treatment so that it is possible for informal actors to do it. In this study, how big is the potential environmental impact of electric motorcycle battery waste repair treatment?

The structure of this article is as follows: Section 2 reviews related work in assessing the potential environmental impact and treatment of battery recycling. Section 3 discusses the proposed methodology. Section 4 presents the results and insights, followed by a comprehensive discussion. Section 5 concludes the paper with critical findings and suggestions for future research

2. RELATED WORK

The literature studied (Table 1) shows that waste management issues and the application of circular economy principles in the small and medium-sized enterprise (SME) sector have become a major focus in recent years. Various types of waste such as construction waste [25], [26], [27], plastic [28], [29], [30], [31], electronics [14], [32], [33], batteries [34] to electric vehicle materials [14], [28] have been studied using various approaches, ranging from green accounting methods [25], barrier factor analysis [26], to feasibility studies [27] and economic models [14], [28].

Research by Rumambi *et al*. [25] and Badraddin *et al.* [26], [27] highlights the importance of reuse, recycle, refurbish, and repair practices in reducing environmental impacts and increasing resource efficiency in the construction sector and related industries. In addition, there is a trend of using advanced technology and analysis methods such as pyro-hydro metallurgy [29], [32], [33] for processing electronic waste and batteries in addition to recycling treatments such as reuse, refurbishment, and repair. These studies also emphasize the importance of life cycle analysis (LCA) [33], material flow analysis [34], and modularization approaches [35] in supporting the sustainability and competitiveness of SMEs.

The literature reviewed includes studies conducted in various countries, such as India, Malaysia, Serbia, and Europe, shows that the challenges and opportunities for implementing a circular economy in SMEs are greatly influenced by local context, policies, and technological readiness [26], [27], [29], [30]. In general, this literature review shows that the integration of the 4R principles (reuse, recycle, refurbish, repair) and the use of appropriate analysis methods are key to waste management and sustainable business development in the SME sector.

3. RESEARCH METHODS

This section explains the rationale for the application of specific approaches, methods, procedures or techniques used to identify, select, and analyze information applied to understand the research problem/project, thereby, allowing the readers to critically evaluate your project's/study's overall validity and reliability.

Steps for assessing the potential environmental impacts of treatment repair using ISO 14044. Life Cycle Assessment (LCA) is a methodology used to assessment the potential environmental impacts of a product or service throughout its life cycle, with a "start-to-end" approach. LCA allows to (i) assess the environmental burden associated with a product, process or activity, by identifying and quantifying energy and material hotspots and (ii) identifying and evaluating opportunities for environmental improvement [19]. The study in this article uses the ISO 14044 standard procedure. The LCA stages consist of four stages (Fig. 1). These four stages are: (1) Determining the objectives and scope of the study; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA); and (4) Interpretation of the results.

The scope of the study in this article is "gate-to-gate". The assessment begins when the battery is declared EoL. The assessment ends when the maintenance repair process is complete and the battery is ready for use in an electric motorcycle.

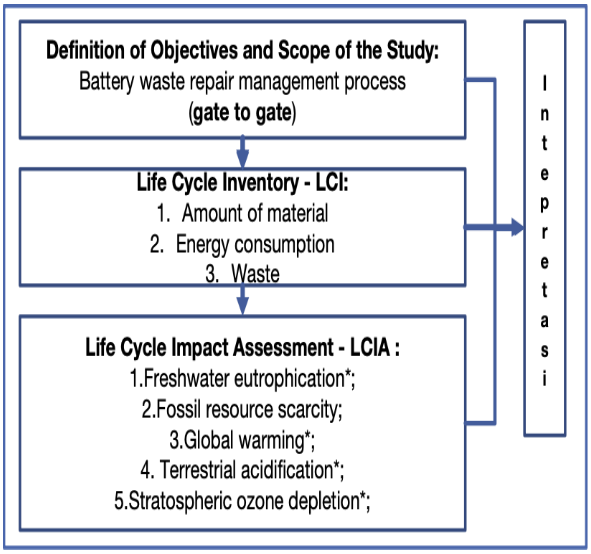

Fig 1. Flowchart of waste battery life cycle study

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Table 1. Literature study

No	Authors	Year	Waste	Reuse	Recycle	Refurbish	Repair	Method	SME
1.	Rumambi *et al.* [25]	2023	Construction waste	v	v		v	Green Accounting	SME
2.	Giridhar & Panicker [29]	2023	Pen		v (Pyro-hydrometallurgy)			NASA - TLX	SME in India
3.	Chaudhuri *et al.* [30]	2022	Plastic waste	v				Resource Based Value	SME recycling plastics business
4.	Badraddin *et al.* [26]	2022	Concrete		v			Barrier factors	SME in Malaysia
5.	Abdullah [28]	2021	Material from EoL EVs		v	v		Feasibility study	SME with recycling business
6.	Dany *et al.* [31]	2021	Plastic HDPE		v			Design of experiment	SME
7.	Badraddin *et al.* [27]	2021	Concrete		v			Analysis factor	Construction SMEs
8.	Wu *et al.* [19]	2021	Plastic waste	v	v			Qualitative research	SME in Taiwan
9.	Mandić *et al.* [33]	2019	Electronic waste		v (Pyro-hydrometallurgy)			Lifecycle Assessment	SME in Serbia
10.	D'Adamo *et al.* [36]	2019	Waste electrical and electronic equipment		v (Pyro-hydrometallurgy)			Economic model	SME
11.	Balakrishnan *et al.* [37]	2018	Metals	v	v			Diffusion analysis	SME in Europe
12.	Bi *et al.* [35]	2015	Not discussed waste specifically	v	v	v	v	Modularization and reconfiguration	SME
13.	Dunn *et al.* [34]	2021	Battery	v	v			Material Flow Analysis	Laboratory
14.	Kurdve *et al.* [14]	2019	Electric Vehicle				v	PESTLE	OEM
15.	This Research	-	End of life battery NMC and LFP				v	LCA for gate-to-gate assessment	SME (Electric vehicle repair shop

4. RESULTS AND DISCUSSION

4.1. Definition of objectives and scope of the study

The definition of objectives and the scope of the study is carried out so that the assessment process becomes clear and consistent, so that the results of the study that will be recommended are appropriate. In determining the scope of the LCA study, it is necessary to consider the system of the product to be measured or evaluated, the functional unit (FU) of the product, the reference flow of materials, the boundaries of the product system, data requirements, assumptions and types of environmental impacts. The FU is a measure of the functional output performance of the product system.

a. NMC Type Battery b. LFP Type Battery

Fig 2. Electric motorcycle battery with 1.0 kWh functional unit

The purpose of this study is to assess the potential environmental impact of electric motorcycle battery waste management on treatment and repair for batteries with a FU battery of 1.0 kWh. This assessment is expected to obtain the value of the potential environmental impact of battery waste management and can extend the life cycle of the battery so that it does not stop as battery waste.

In this study, the assessment of the potential environmental impact will be carried out on the product system of two types of batteries that are currently widely used in electric motorcycles in Indonesia. The two types of batteries are NMC and LFP with the same FU (60V 23 Ah: Viar Q1 and Volta 401) (Fig. 2).

The treatment considered in this study is the repair treatment, as a simple treatment [9], [38], both in terms of investment and worker expertise, but it can extend the battery life as a motor drive battery. The scope of the study, as the purpose of the study, is to assess the potential environmental impact of the battery waste treatment repair product system on the electric motorcycle battery supply chain. The electric motorcycle battery supply chain can be seen in Fig. 3, while the scope of the study is the area with the red dotted line. The scope of this kind of LCA is gate-to-gate. The assessment is carried out from when the battery is declared as waste until the battery is ready to be reused as a traction battery in its second life. The product system from the scope of the study can be seen in Fig. 4 and Fig. 5. Both product systems are product systems that occur in EC workshops in Yogyakarta.

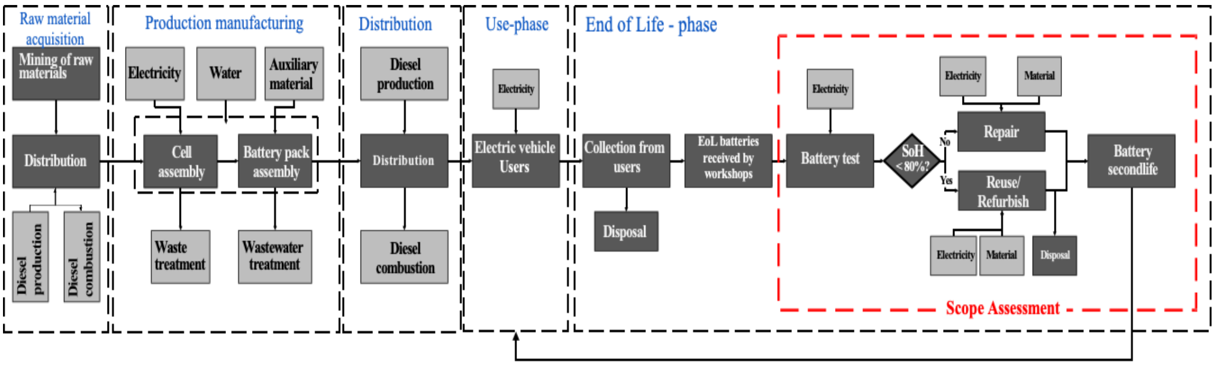

Fig. 3 Scope of the study on the battery supply chain

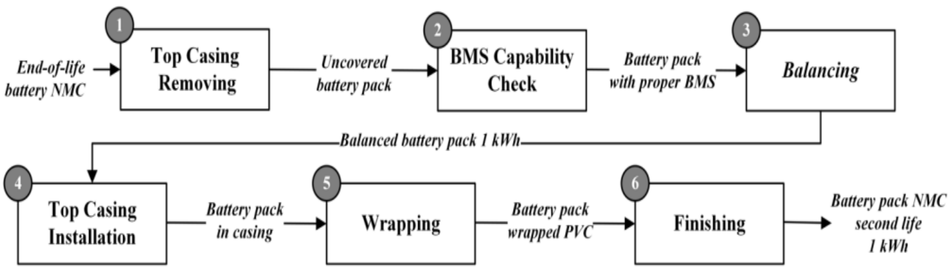

Fig 4. NMC treatment repair product system

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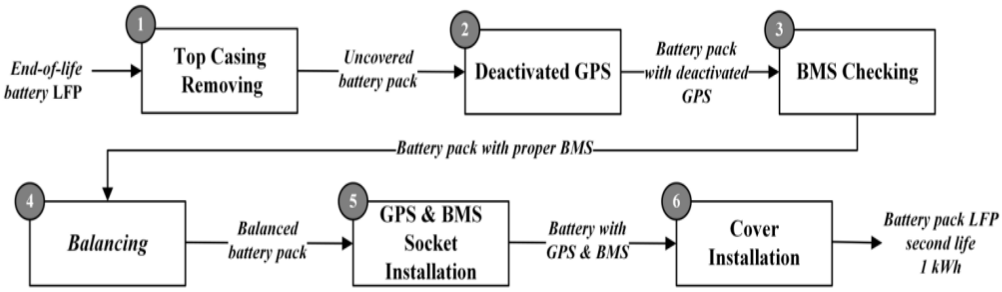

Fig 5. LFP treatment repair product system

4.2. Life cycle inventory (LCI)

Life cycle inventory involves the process of collecting data and calculating the inputs and outputs generated throughout the process or system of a 1.0 kWh electric motorcycle battery product. LCI aims to identify and measure the amount of material, energy, and waste. LCI data is obtained from primary and secondary data. Primary data is identified and measured when carrying out the practice of dismantling battery waste at the EC Yogyakarta workshop. Experts at the workshop verified the accuracy and suitability of the components using Google browser literacy. While secondary data is the determination of material characterization values using the Ecoinvent 3.8 database. Secondary data is selected with input from experts from institutions that usually conduct life cycle assessments.

Inventory in the repair treatment phase is carried out by first building a battery product system. The product system generally begins with the dismantling process, BMS inspection, balancing, and reassembly. The detailed product system of NMC and LFP type repair treatment can be seen in Fig. 6 and Fig. 7. At this stage, detailed recording of the materials and energy required and the waste generated in the repair treatment for both types of batteries is carried out. Table 2 and Table 3 are tables of repair treatment inventory for NMC and LFP type batteries. Based on Fig. 4 and Fig. 5 and Table 2 and Table 3, both product systems consist of six steps.

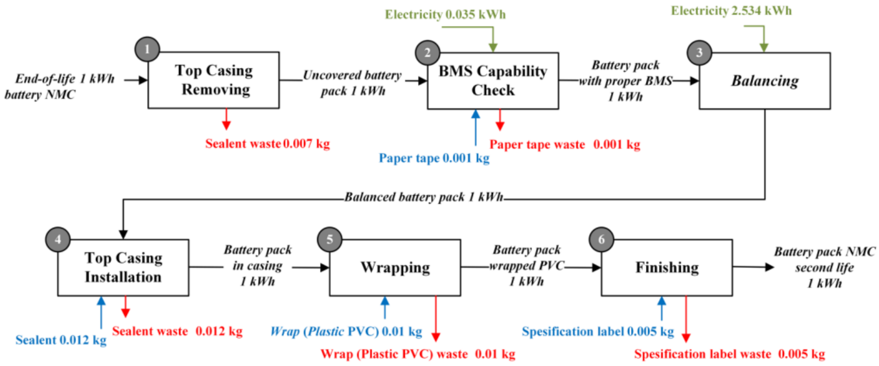

Fig 6. NMC repair treatment mass and energy balance

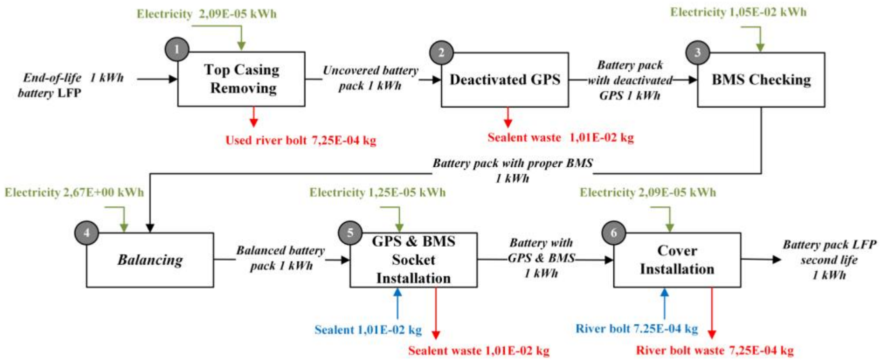

Fig 7. LFP repair treatment mass and energy balance

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Table 2. Inventory treatment repair NMC

Input/Output	Total	Unit	Quantity per FU	Unit	Percentage	Dataset Ecoinvent 3.8
Input						
Material						
End-of-life Lithium Ion Battery Pack (NMC 811)	10.000	kg	7.13E+00	kg/kWh	100.00%	market for used Li-ion battery | used Li-ion battery | APOS, S - GLO
Support Material						
Paper tape	0.001	kg	7.07E-04	kg/kWh	3.57%	market for kraft paper | kraft paper | APOS, S - RoW
Sealent	0.012	kg	8.48E-03	kg/kWh	42.86%	market for polyurethane adhesive | polyurethane adhesive | APOS, S
Wrap (Plastic PVC)	0.010	kg	7.07E-03	kg/kWh	35.71%	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised | APOS, S
Specification label	0.005	kg	3.53E-03	kg/kWh	17.86%	market for cellulose fibre | cellulose fibre | APOS, S - RoW
Energy						
Electricity	7.652	kWh	5.41E+00	kWh/kWh	100.00%	market for electricity, high voltage | electricity, high voltage | APOS, S - ID
Output						
Product						
Battery Pack LFP Second Life	1.415	kWh	1.00E+00	kWh/kWh	100.00%	-
Waste						
Paper tape waste	0.001	kg	7.07E-04	kg/kWh	2.63%	treatment of waste graphical paper, municipal incineration | waste graphical paper | APOS, S - RoW
Sealent waste	0.022	kg	1.55E-02	kg/kWh	57.89%	treatment of waste polyurethane, sanitary landfill | waste polyurethane | APOS, S - RoW
Wrap (Plastic PVC) waste	0.010	kg	7.07E-03	kg/kWh	26.32%	treatment of waste polyvinylchloride, sanitary landfill | waste polyvinylchloride | APOS, S - RoW
Specification label waste	0.005	kg	3.53E-03	kg/kWh	13.16%	treatment of waste polyvinylchloride, sanitary landfill | waste polyvinylchloride | APOS, S - RoW

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Table 3. Inventory treatment repair LFP

Input/Output	Total	Unit	Quantity per FU	Unit	Percentage	Dataset Ecoinvent 3.8
Input						
Material						
End-of-life Battery LFP	11.000	kg	7.97E+00	kg/kWh	100.00%	
Support Material						
Sealent	0.014	kg	1.01E-02	kg/kWh	93.33%	market for polyurethane adhesive | polyurethane adhesive | APOS, S
River bolt	0.001	kg	7.25E-04	kg/kWh	6.67%	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | APOS, S - GLO
Energy						
Electricity	3.705	kWh	2.68E+00	kWh/kWh	100.00%	market for electricity, high voltage | electricity, high voltage | APOS, S - ID
Output						
Product						
Battery Pack LFP Second Life	1.380	kWh	1.00E+00	kWh/kWh	100.00%	-
Waste						
Sealent waste	0.014	kg	1.01E-02	kg/kWh	93.33%	treatment of waste polyurethane, sanitary landfill | waste polyurethane | APOS, S - RoW
River bolt waste	0.001	kg	7.25E-04	kg/kWh	6.67%	treatment of used outside air intake, stainless steel, DN 370 | used outside air intake stainless steel, DN 370 | APOS, S - RoW

4.3. Life cycle impact assessment (LCIA)

LCIA aims to produce evaluation values that provide estimates of the potential impacts of a product system. At this stage, an environmental impact assessment is carried out by involving a series of environmental impact measurement steps following ISO 14042 [39], starting with selecting and defining impact categories, characterization, assessment and normalization. At the LCIA stage, environmental impacts are determined based on the inventory that has been carried out previously. The LCIA method used is ReCiPe 2016. ReCiPe is a development method of the Eco-indicator 99 and CML-IA methods, which were initially developed to integrate problem-oriented approaches as the midpoint and damage as the endpoint [32]. Impact assessment translates emissions and material extraction into a number of environmental impact scores called characterization factors. ReCiPe 2016 reduces characterization factors to two levels: (1) 18 midpoints and (2) 3 endpoints.

In this study, from the eighteen midpoint categories provided by ReCiPe 2016, five midpoint impact categories were used or selected. The five impact categories represent the three endpoint categories consisting of: 'impact on human health'; 'impact on the environment'; and 'impact on resource availability'. The selection of the midpoint is based on the life cycle assessment criteria (Regulation of the Minister of Environment and Marine Affairs of the Republic of Indonesia No. 1 of 2021) and the Koroma article [13]. In the endpoint category, the impact on health chosen is global warming. The impact on the environment is selected freshwater eutrophication, terrestrial acidification, and ozone depletion. Meanwhile, for the impact on resource availability, the midpoint impact categories chosen are mineral resources and fossil resources.

Next is characterization, grouping of midpoints and normalization. Characterization refers to the inventory (Table 2 and Table 3) of input, output, and waste databases. The characteristic factor (CF) value in the database is used to calculate the contribution of each input/output to a particular environmental impact. Then grouped according to relevant categories into characterization results. After obtaining characterization results, based on the impact category (ReCiPe 2016) will be the midpoint impact value. The results of the Environmental Impact Assessment on all treatment repair steps can be seen in Table 4. The five potential environmental impact values will affect human health, the environment, and resource availability. In general, from both types of batteries, NMC appears to be more dominant for all measured impact values compared to LFP.

Table 4. Impact assessment repair result

No	Impact category	NMC	LFP	Unit
1	Fossil resource scarcity	0.848	0.384	kg oil eq
2	Freshwater eutrophication	0.006	0.00646	kg P eq
3	Global warming	**3.386**	**1.57**	kg CO2 eq
4	Stratospheric ozone depletion	0.0000014	0.000000394	kg CFC11 eq
5	Terrestrial acidification	0.017	0.00002	kg S02 eq

Table 5. Normalization results repair NMC

No	Impact category	Characterization results	Normalization values	Normalization results
1	Freshwater eutrophication	0.006	0.65	0.009245
2	Fossil resource scarcity	0.848	980.39	0.000865
3	Global warming	3.386	7990.41	0.000424
4	Terrestrial acidification	0.017	40.98	0.000415
5	Stratospheric ozone depletion	0.0000014	0.06	0.000023

Table 6. Normalization results repair LFP

No	Impact category	Characterization results	Normalization values	Normalization results
1	Freshwater eutrophication	0.006	0.65	0.0099385
2	Fossil resource scarcity	0.384	980.39	0.0003917
3	Global warming	1.570	7990.41	0.0001965
4	Terrestrial acidification	0.00000039	0.06	0.0000066
5	Stratospheric ozone depletion	0.00002	40.98	0.0000005

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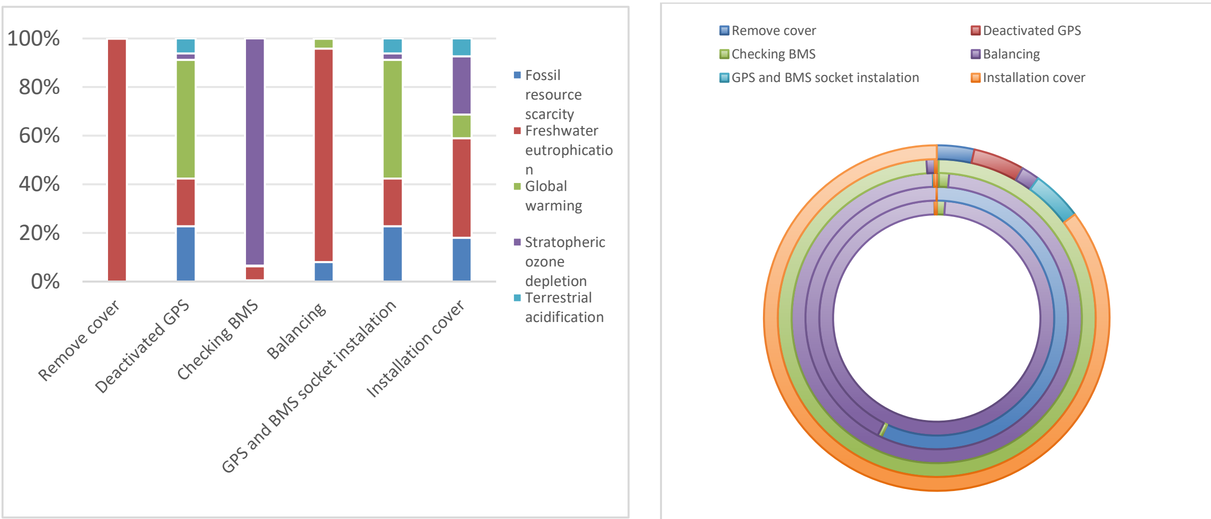
Furthermore, the results of the characterization results are normalized to show the extent to which the impact category results have relatively high or low values when compared to a reference value. Normalization is done to facilitate comparison between different impact categories through the same lens. Normalization is done by dividing the characterization results by the normalization values. Normalization values are obtained from the openLCA software by selecting the impact assessment method ReCiPe 2016 Midpoint. The calculation of the normalization results from the LCA values in the repair treatment of the two types of batteries that have been sorted from the largest value is presented in Table 5 and Table 6. From the two tables, it appears that the NMC and LFP battery product systems in the repair treatment show the greatest potential environmental impact in the freshwater eutrophication category, followed by the fossil resource scarcity and global warming categories.

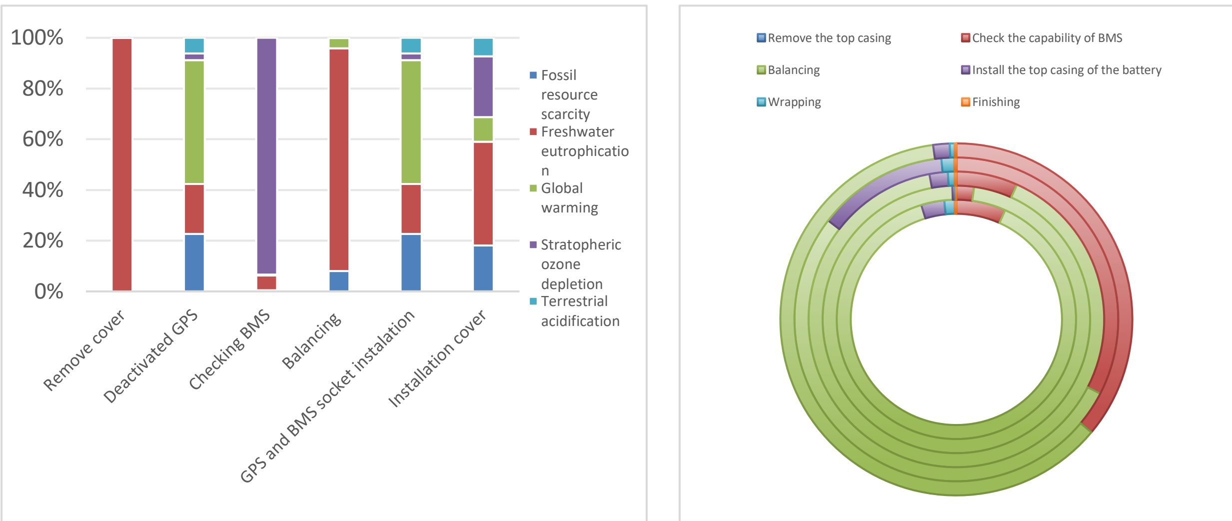
The processes that have the potential to cause major impacts are processes that require electrical equipment, such as balancing, BMS inspection, and removing the top cover on LFP batteries. Based on Fig. 8 and Fig. 9, the greatest potential impact on both the NMC and LFP battery product systems is the battery balancing process. The process of opening or dismantling the top cover is the second contributor to the impact. In both the NMC and LFP battery product systems, the dominant impact category is freshwater eutrophication (light blue bar).



a. Normalization results of the potential environmental impact of NMC

b. Potential environmental impact on the NMC repair process

Fig. 8. Potential environmental impact of NMC



a. Normalization results of the potential environmental impact of LFP

b. Potential environmental impact on the LFP repair process

Fig 9. Normalization results of the potential environmental impact of LFP

Fig 10 shows that the potential impact of the NMC product system is significantly greater than that of the LFP product system. Higher potential impacts occur in all categories of impacts assessed. The freshwater eutrophication category contributes quite significantly to the possibility that this excess is related to the casing removal process using electric drills. This is in accordance with what was conveyed by Xin Lin *et al.* [40], that the impact of freshwater eutrophication is more due to the source of electricity. Based on the figure, it can also be stated that the potential impact of remedial treatment has a greater influence on the end point of ecosystem damage, resource scarcity, and ultimately on human health damage (Table 7).

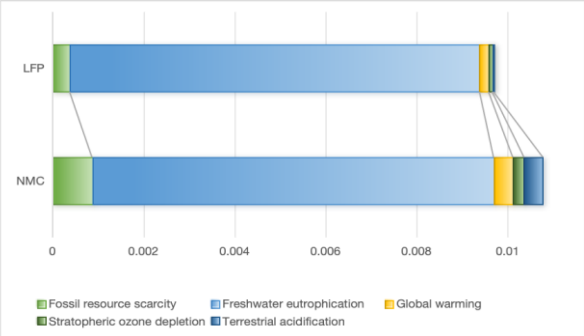


Fig 10. Potential environmental impacts of treatment repair for NMC and LFP

Both NMC and LFP batteries have been shown to contribute to this greatest impact. Based on the Cusenza article, this freshwater eutrophication impact category is found in the battery production phase, usage phase, and waste treatment phase. These three phases predominantly require electrical energy. Repair treatment has a main balancing process that requires quite a lot of electrical energy, which is around 7.602 kWh for NMC batteries and 3.69 kWh for LFP batteries. In addition, this LFP battery is designed for ease of dismantling or removing the casing. The connection between the main casing and its cover uses rivet bolts. Dismantling can be done quickly with the help of an electric drill, with an energy of 2.89 × 10^-5 kWh. For NMC batteries, they are simply manually disassembled because the casing connection uses glue. The problem occurs when you have to deactivate GPS on the LFP battery, which is not available on the NMC battery. This LFP battery is not equipped with an instruction manual, so the deactivation process carried out by the workshop is relatively long. In addition, LFP products with the main element of phosphate cathodes, of course, cumulatively contribute to the freshwater eutrophication impact category compared to NMC products.

The resource scarcity category is to assess the availability of fossil resources such as oil, natural gas, and coal. Excessive use of these resources leads to scarcity and increased extraction costs. NMC batteries have a greater resource scarcity impact than LFP batteries. This is because the NMC cathode elements are nickel and cobalt, which are starting to become rare, while LFP uses iron and phosphate, which are still relatively abundant in the world.

Global warming is a category of global environmental impacts. This category is one of the midpoint criteria of the chemical emission impact category, namely the impact of climate change. Based on information from NEEF (National Environmental Education Foundation) [41], global warming is a change in conditions involving global temperatures, shifting weather patterns, rising sea levels, and widespread ecological impacts. This impact occurs in both battery products because, in the gate-to-gate repair treatment scope, the main process is balancing, which requires quite a lot of electrical energy [12]. The electrical energy used is electrical energy from coal, which has an impact on global warming from the exploitation phase to being distributed when balancing is carried out.

Ozone Depletion is a decrease in ozone concentration in the stratosphere due to the release of substances that break down ozone molecules (O_3) [39], [40]. The main causes are the increase in elements: Chlorofluorocarbons (CFCs), which are commonly used in refrigerants (AC, refrigerators), aerosols, and solvents; Halons and Bromine, which are commonly used in fire extinguishers; and Nitrogen Oxides (NO_x) produced from the combustion of fossil fuels and rocket emissions. In this battery waste, the contribution to the impact of ozone depletion is due to the use of electrical energy from coal in several processes in the repair treatment [12]

Table 7. Potential impact results: midpoint - damage – endpoint

Midpoint	**Damage**	**Endpoint**
Freshwater eutrophication* **(kg P-Eq)**	Damage to freshwater species	Damage to the ecosystem
Fossil resource scarcity **(kg oil-Eq)**	Increase extraction cost/energy	Damage to resource availability
Climate change - Global warming potential* **(kg CO_2-Eq)**	Increase in other diseases	Damage to human health
Ozone depletion potential* **(kg CFC-11-Eq)**	Damage to terrestrial species	Damage to the ecosystem
Terrestrial acidification potential* **(kg SO_2-Eq)**		

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Table 8. Potential environmental impact of global warming

Category	NMC	LFP	Unit
Number of EoL batteries in 2024	18,000	18,000	unit
GWP repair treatment per battery	3.386	1.57	kg CO_2 eq
GWP for all EoL batteries 2024	60,948	28,260	kg CO_2 eq
Total GWP of repair treatment	89,208		kg CO_2 eq
Global emission reduction target	420 x 10^9		kg CO_2 eq
GWP contribution from repair treatment	0.000021%		

Terrestrial acidification is a decrease in soil pH due to the accumulation of hydrogen ions (H^+), which reduces soil fertility and damages terrestrial ecosystems [42]. This process is mainly caused by acid deposition from human and natural activities, as well as the release of acid-triggering compounds during waste processing. The causes include: Acid Gas Emissions (SO_2, NO_x, NH_3), which come from the combustion of fossil fuels (coal, oil) releasing sulfur dioxide (SO_2) and nitrogen oxide (NO_x), which react with water in the atmosphere to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3); The use of nitrogen fertilizers and ammonia (NH_3) increases the release of acidic compounds into the soil; Mining and processing of metal materials (nickel, cobalt). KÏopffer & Grahl [43] and Liu *et al.* [44] state that battery waste, especially the NMC type, contributes to the terrestrial acidification impact category because the cathode elements in NMC are nickel and cobalt.

During the NMC battery production phase, large amounts of energy are required, especially for metal extraction and cathode material synthesis. In general, both types of battery cathodes use energy from fossil-based power plants, where nitrogen oxide emissions from fuel combustion can contribute to acidification indirectly. The environmental impact that is in the global spotlight is the global warming category. The NMC product system contributes to the third rank in the global warming category; the same category in the LFP product system is the fourth rank.

Table 8 illustrates the calculation of the potential global warming impact of battery EoL repair treatment. Literature BU-808 [45] states that lithium batteries reach EoL after 300-800 cycles of use, equivalent to 1-4 years. The calculations in this article use average values, so EoL is after 2 years of use. Based on 2022 sales data and the assumption of 40% additional batteries for the 2022 electric motorcycle population, the estimated EoL for 2024 is 36,000 batteries. This additional number of batteries comes from electric motorcycle owners with two batteries and from electric motorcycle conversions. The next assumption is that the number of electric motorcycles using NMC and LFP types is comparable. Therefore, the number of EoL NMC and LFP batteries in 2024 is 18,000 batteries each. The calculated potential global warming impact of repair treatment for both battery types can be said to be relatively small.

This article selects the category of global warming, which is a global indicator and impacts human health endpoints. Global emission reduction targets are set through various international agreements, including the Paris Agreement [43]. In general, countries are committed to limiting global warming to a maximum of 1.5 degrees Celsius above pre-industrial levels. The 1.5 °C reduction that is the target is equivalent to 420 giga kg CO_2 eq. Based on data on the number of electric motorbikes in 2020 for NMC and LFP type batteries (Table 7), assuming the end of battery life is four years, it is estimated that in 2024, it will contribute 89,208 kg CO_2 eq, or equivalent to increasing 0.000021% of the global emission reduction target.

According to Information from the Indonesian Ministry of Energy and Mineral Resources, the transition from fossil fuel vehicles to electric vehicles has the potential to reduce fossil fuel use by 6 million kiloliters per year and reduce greenhouse gas emissions by 7.23 million tons of CO_2 [23] or equivalent to 1.72%. The LCA results show that the impact contribution from 18,000 NMC battery waste and 18,000 LFP battery waste is still relatively small. The number of electric motorbikes currently has not reached the target set by the government of the Republic of Indonesia, which is 8,400,000 units in 2030. However, if this number is reached, treatment and repair will contribute a potential global warming impact of 0.0050%, a 233-fold increase from the current level. It will have other potential environmental impacts, namely ecosystem damage, resource scarcity, and increased human health.

Based on the interpretation of the LCA results, the five potential environmental impacts are rooted in the use of electrical energy in several processes when carrying out repair treatment or balancing. Learning from several developed countries regarding hazardous and toxic materials waste management [10], [38], a possible solution that can be recommended is recycling managed by the state, with the assistance of manufacturers. The state needs to build regulations that will protect the ecosystem, society and users of electric motorbikes [7]. The state must build a recycling industry and battery waste collectors in several regions.

Affordable recycling costs and standard processes. Some efforts that manufacturers must make are:

1) Centralized control by manufacturers: manufacturers strive to maintain centralized control over vehicle usage data and system information to maintain manufacturer responsibility for design, component life cycle, to repair tools [8], [38].
2) Manufacturers can collaborate with informal actors in the form of an OEM-workshop collaboration model. This collaboration can include training and the use of standardized equipment. Collaboration is also possible in the form of business partnerships that can be replicated at several locations in Indonesia [20].
3) Manufacturers are responsible for batteries: in monitoring battery status periodically, how to repair and dismantle it, and deciding on the eligibility for a second life of the battery [8]. This management is expected to better maintain battery quality so that it provides good performance when entering its second life [7].
4) Battery ownership business model: battery ownership may lie with the manufacturer; in this case the customer buys the vehicle but rents the battery, with a monthly price associated with the annual mileage (swapable battery) [8].
5) Battery waste management: the dismantling procedure is risky and dangerous due to the high voltage of the package, requires trained technicians and special technology with robotics so that the process becomes effective and efficient [10] and reduces the risk of serious failure.
6) Use of alternative energy as a source of electrical energy: The use of sources of electrical energy materials other than coal is expected to reduce the five categories of impacts, especially global warming, freshwater eutrophication, and ozone depletion [10], [44].

This article is initial research in supporting government efforts to create a circular economy. Optimal involvement of several actors in the supply chain is expected to strengthen the circular economy and be sustainable. For this reason, some future research that needs to be done is designing batteries that facilitate periodic battery monitoring, repair, dismantling and reuse. Designing service standards for management by maintaining the safety of electric motorbike users, improving battery performance, and optimal costs for managers and users.

5. CONCLUSION

The practices implemented by informal actors in the product treatment and repair system are still considered safe, with a GWP impact contribution of 0.000021%. Therefore, they can be used as a model for new informal actors. The availability of battery waste management facilities is expected to accelerate the transformation from fuel-based vehicles to electric vehicles.

The government needs to immediately formulate regulations for electric motorcycle manufacturers, as it is hoped that more adequate technology and standards will further reduce environmental impacts. The government also needs to prepare adequate battery waste processing facilities immediately.

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