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Review article

Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing

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ABSTRACT

Climate change is a significant global environmental issue that has attracted extensive research and debate. Consequently, the concept of sustainability in the context of aluminium encompasses multiple dimensions. Within the discussions surrounding waste and resource management, there is ongoing deliberation about the actual environmental advantages offered by material recycling. The high demand for raw materials has prompted researchers to explore sustainable recycling processes, with a particular focus on processing technologies. A comprehensive examination of these diverse methods is crucial for understanding three main techniques for aluminium forming: conventional recycling (CR), semi-direct recycling (SDR), and direct recycling (DR). Through a systematic review, it becomes evident that SDR and DR, which incorporate a forming process, present substantial environmental, energy, and cost benefits while promoting sustainability awareness in the manufacturing sectors. This extensive review also encompasses nine life cycle analysis (LCA) studies, comprising sixteen scenarios that have employed various methodologies to assess the environmental impact of managing waste aluminium through different approaches: recycling (melting and solid-state), incineration, or landfill. The outcomes of this comprehensive international review provide a more unbiased evaluation of the environmental effects associated with various wastes management systems. The majority of the studies indicate that recycling offers superior environmental solutions and fewer environmental effects compared to alternative waste green forming management options.

1. Introduction

The world has become increasingly aware of the detrimental impacts of human activities on the environment. Manufacturing, in particular, has been identified as a significant contributor to negative environmental impacts. Nevertheless, it is not possible to disregard the importance of manufacturing. As a global reduction of carbon dioxide emissions generated by greenhouse gas production becomes more crucial in preventing global warming, optimising energy consumption in industrial processes, transportation, and production engineering has become critical in today's industrial world [1,2]. Since the industrial revolution in the 18th century, it has been widely acknowledged that the manufacturing industry has negatively affected the environment. As a result, several laws and policies focused on environmental preservation have been put in place, such as the Kyoto Protocol, the Montreal Protocol, and the Malaysia Environment Quality Act. These policies include

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specific regulations that aim to decrease the emission of greenhouse gases, thereby helping to mitigate human-induced global warming. In the year 2010, industrial processes were accountable for approximately 14 % of total carbon dioxide emissions and 20 % of overall greenhouse gas emissions [3]. According to Jayal, Badurdeen, Dillon, and Jawahir et al. [4], achieving sustainability in the manufacturing sector, which serves as the foundation of the industrial economy, is crucial for maintaining the high standard of living achieved by industrialised societies. In addition, it plays a crucial role in enabling developing societies to achieve and maintain comparable levels of prosperity. As a result, there is an urgent requirement to decrease energy usage in industrial processes, transportation, and production engineering, which has become a significant motivating factor in the contemporary industrial realm. Furthermore, concerns like haze and air pollution resulting from human activities, water-related issues concerning both quantity and quality and improper handling of toxic and hazardous waste have gained considerable public interest [5,6].

Agamuthu & Fauziah et al. [7] have demonstrated that even after approximately 20 years of abandonment, a former disposal landfill remains contaminated with arsenic and mercury levels that surpass the Dutch Intervention values. This poses a risk to plants, as they can accumulate these contaminants, which can then enter the human food chain. Emissions from landfills, particularly landfill gas (LFG) and leachate, are directly influenced by the quantity and quality of waste disposed. In developing nations, around 65–80 % of collected municipal solid waste is sent to landfills [8–10]. A large amount of municipal solid waste is dumped in landfills in many countries that are developing. In India, for example, just 12 millions of the 62 million tonnes of trash produced yearly are handled, whereas the majority is dumped in landfills. About 70 % of the rubbish is collected. Similar problems with waste management exist in Brazil, where a significant quantity of garbage from municipalities is improperly handled and ends up in landfills or open dumps. Significant amounts of neighbourhood trash are also deposited in landfills in Nigeria, usually in an unregulated manner that creates dangers to both the environment and health. Other challenges are faced by countries including Indonesia, the Philippines, Kenya, Egypt, and Pakistan, which primarily depend on landfills as a result of insufficient waste disposal procedures and infrastructure. To tackle such issues, waste management systems must be greatly enhanced, infrastructure must be improved, and sustainable waste processing technologies must be used [11].

Compared to primary production, recovering aluminium greatly reduces power consumption and carbon dioxide emissions, but there are still several environmental issues to be resolved. These include the usage of energy and consequent CO_2 emissions, the contamination of waste materials that require the use of resource-intensive cleaning techniques, and the generation of potentially hazardous byproducts such as salt slag and metal. Pollution of the atmosphere from particulate matter and harmful emissions is still a worry, and water usage and possible water contamination from recycling procedures also pose threats to the environment. It is also necessary to deal with financial and social issues, such as the impacts on the area's health and workers in the unauthorised recycling sector. To reduce these obstacles and improve the environmental advantages of recycling aluminium, technological developments, more stringent laws, and environmentally friendly activities are crucial [12].

Tatsuhiko Aizawa et al. conducted a study highlighting the production of small and thin-walled aluminium alloy parts using the Pin-Injection-Gate (PIG) die-casting and hot stamping techniques. They utilized granules of pure aluminium and aluminium alloy as a model for recycled materials [13]. Hence, it is of utmost importance to implement appropriate measures to prevent potential environmental hazards and health risks associated with future landfill operations. At present, rising waste management expenses, the acquisition of suitable landfill sites, and the reduction and purification of energy consumption have emerged as significant sustainability concerns.

When compared to other material categories, metals demonstrate the greatest potential for systematic recycling due to several factors. First, metals possess high economic value, enabling cost-effective recycling processes. Second, they are available in large volumes, which allows for economies of scale in recycling operations. Finally, metals possess exceptional recyclability, making them a preferred choice for recycling initiatives [14].

Aluminium, which is the Earth's third abundant element after oxygen and silicon, is witnessing a growing demand. This is mainly attributed to its beneficial characteristics, such as exceptional resistance to corrosion, high strength, and low density in comparison to steel. As a result, the utilization of aluminium, a lightweight material, is frequently considered a favorable choice for improving fuel efficiency in transportation applications. As a rough estimate, a 10 % reduction in weight leads to approximately a 5 % enhancement in fuel efficiency [15,16].

To give a thorough summary of the environmental effects of creating one tonne of aluminium alloy (for both casting and forging), The indicators related to social and biological variety as well as the main substances energy consumption, CO_2 emissions, water consumption, and toxicity. In LCA, biodiversity indicators are essential for assessing the environmental effect of manufacturing processes, such as casting and forging, which are procedures used to produce aluminium. High-impact studies underline how crucial it is to include biodiversity measures in LCA frameworks, such as changes in land use, water usage, and pollutant emissions. Throughout the life cycle of the product, these indicators aid in quantifying the effects on ecosystems, species richness, and environmental quality. When these metrics are combined, LCA can offer a more thorough knowledge of the environmental impact. This can help enterprises adopt more sustainable practices and encourage conservation of biodiversity in tandem with technological developments in industrial processes.

Aluminium offers numerous benefits over ferrous materials, including ductility, malleability, corrosion resistance, superior conductivity, low density, and, most notably, its recyclability. The recyclability of aluminium is a critical factor that contributes to its extensive utilization in the manufacturing industry, particularly in the automotive sector.

On the contrary, Schlesinger et al. [17] found that the production of aluminium, which involves extracting bauxite (a primary resource), requires a substantial amount of energy, approximately 200 GJ/ton-1. This energy requirement is nearly 10 times higher than that of steel production, resulting in virgin aluminium being five times more expensive than steel. Consequently, aluminium recycling is necessary due to its significantly improved cost-effectiveness when compared to primary resource utilization. It is estimated that producing a given mass of aluminium from recycled scrap (secondary resources) requires only 5 % of the energy needed to produce the same mass from bauxite (primary resources).

The economic benefits of recycling aluminium alloys have been demonstrated to be substantial. Hence, it is crucial for the aluminium industry to create and employ technologies that maximize the advantages of recycling. The most commonly utilized practices for recycling aluminium in different industries revolve around the conventional recycling (CR) method. This method entails melting the alloy to generate a secondary ingot that possesses a controlled composition, aligning with standardized grades. The CR technique involves various stages, such as cleaning, cutting, and shaping the final product.

Hatayama et al. [18] projected that by 2030, approximately 6.1 megatons of scrap will go unrecycled due to the high concentration of aluminium alloying elements, which are challenging to efficiently remove during remelting. Oxidation during the melting or recycling of chips and scraps leads to a significant loss of aluminium alloy [19]. Samuel et al. [20] examined material losses at each stage of the recycling process, highlighting losses resulting from mixing with the slag on the melt's surface, scrap generated during casting, and subsequent processing of aluminium ingots. Collectively, these losses can reduce aluminium yield to as low as 54 % [21].

Moreover, conventional recycling methods involve melting aluminium alloy chips and scraps, necessitating heating to elevated temperatures exceeding 1,000 K [22]. The costs associated with environmental protection measures have further contributed to overall expenditures [23].

Various innovative approaches have been proposed for recycling aluminium chips using solid-state recycling techniques. Initially, Gronostajski et al. [24] and later Fogagnolo et al. [25] introduced solid-state recycling methods utilizing powder metallurgy processes. However, more recent advancements have improved the solid-state technique by eliminating the ball-milling process and instead producing fine granulated particles. This modified process requires only 5–10 % of the energy compared to the conventional process, which involves remelting the scrap to create new extrusion billets [26]. This reduction in energy consumption leads to cost savings, as the material is directly recycled from the chips through hot forging, resulting in a more economically viable process. Samuel et al. [20] summarized this technique in fewer steps, demonstrating improved recovery efficiency and reduced generation of new scrap. Gronostajski et al. [19] reported that this technique achieved a 95 % recovery rate, utilized only 5–6 GJ of energy per ton, and required only 2.5–6.5 man-hours per ton.

Another comprehensive investigation demonstrated the viability of using hot forging to enhance the strength and plasticity of recycled aluminium. This study supports the solid-state technique combined with hot forging as a viable alternative for recycling aluminium alloy chips. Further research in this specific field is strongly recommended due to its potential implications for environmental conservation [1,27].

On the subject of waste management, it is a globally recognized and concerning issue. Landfilling, incineration, and recycling are three common practices employed in the management of aluminium waste. It is our responsibility to select the appropriate approach in handling aluminium waste to contribute to environmental conservation and preservation. Life Cycle Assessment (LCA) is a commonly used and globally recognized approach to evaluate the environmental consequences of products and systems. In recent times, LCA has been widely applied to compare the environmental impacts of different waste management choices. The aim of this study is to identify and examine previous LCA investigations that explore alternative waste management options specifically for aluminium.

In the majority of industries, the prevailing method for recycling aluminium involves melting the scrap to produce a secondary ingot with a controlled alloy composition that aligns with standardized grades. However, a recent study highlights that a considerable amount of scrap, approximately 6.1 megatons, will not be recycled by the year 2030 due to the high concentration of alloying elements [18]. The removal of certain elements during the remelting of aluminium scrap presents difficulties, leading to the exploration of an alternative method called solid-state recycling. This approach, which avoids the melting process, has gained attention due to its environmental benefits, particularly in reducing metal losses. Based on this, the author proposes considering the inclusion of solid-state recycling, specifically meltless phase recycling, in life cycle assessment (LCA) findings to assess its environmental impact and contribute to environmental preservation. This extensive review involves nine life cycle analysis (LCA) studies that cover sixteen possibilities. The studies employ a variety of approaches to evaluate the environmental impact of different aluminium waste management strategies. The structure of this paper is outlined as follows: Section 2 covers the review methodology using systematic analysis. Section 3 explores the potential of aluminum recycling techniques. Section 4 discusses the life cycle assessment concerning aluminum waste management. Finally, Section 5 presents the conclusion and future trends.

2. Methodology

2.1. The analysis of systematic review

Life cycle evaluation research had a big effect on the field of engineering, as it is an important metric that helps the engineering industry figure out how efficient a concept is based on how long it will last and how well it can be used. In the process of life cycle analysis, the impacts and effects of an operation from conception to completion are taken into account. A certain outcome in a very exciting event. Hence, drawing from Refs. [28–30], the main goal of this study was to analyze the available literature following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. The focus was on investigating the implementation of recycling aluminium through direct recycling, semi-direct recycling, hot extrusion, hot forging, and cold forging methods, with the aim of elucidating their effects on different aspects of direct metal recycling advancement for the purpose of achieving sustainability.

2.2. Planning

Research questions focus on the recycling of aluminium using the conventional melting process, semi recycle, direct recycling process addressed in Table 1, which involves melting the alloy to produce a controlled secondary ingot. This technique involves various stages, such as cleaning, cutting, and shaping. The aluminium industry must develop and employ technologies that maximize recycling advantages. Solid-state recycling, specifically melt less phase recycling, should be included in life cycle assessment (LCA) findings to assess its environmental impact and contribute to environmental preservation. Previous LCA investigations should explore alternative waste management options for aluminium.

2.3. Research strategy

Regarding the searching terms, literature background, and methodology, a thorough examination of the search plans utilized in this study has been presented.

2.3.1. Search term analysis

The following search terms were derived from the research being investigated: aluminium recycling, direct recycling, semi-direct recycling, life cycle assessment, and sustainable manufacturing. These terms were utilized to construct the search queries for the study. The final

Table 1
Lists the reasons/motivations for developing a research question.

Research Question	Reasons/Motivation
RQ1: What does research evidence demonstrates the recycling process for melting aluminium alloy?	Assembling the results of prior research into a unified taxonomy to organize and characterize prior work in a methodical manner, producing a concise summary of prior study. In certain ways, the taxonomy component offers all scholars crucial viewpoints on the particular subject.
RQ2: How important of knowledge basis and technique that can support the methods of recycling aluminium in the way of conventional, semi, and direct?	It is crucial to educate researchers about techniques that geometrical elements use to identify certain features, like circular holes, pockets, and planes, which are beneficial for the manufacturing sector.
RQ3: With what technique or processes should the aluminium recycling can be carried out and what factor or variables need to study?	Can be used to demonstrate how SDR and DR, which include a forming process, offer significant financial, energy, and environmental advantages while raising awareness of sustainability in the manufacturing industries.

concepts of the search were as follows for first key ("aluminium recycling *" OR" direct recycle" OR" semi direct recycle"), while second key ("aluminium recycling" AND "hot extrusion" OR "hot forging" OR "cold forging"), and the third key was "Sustainable manufacturing" AND "Direct metal recycling" AND "Powder metallurgy" AND "Hot extrusion" AND "Hot forging" AND "Cold forging" OR "Life cycle assessment".

2.3.2. Existing research and literature resources

Based on the nature of this research, a methodology was devised to conduct a systematic review and gather data from multiple databases containing relevant literature. Three databases, namely Science Direct, Scopus, and IEEE, were selected due to their comprehensive coverage of publications. Searches were performed using "title" and "abstract" keywords to identify published journals and conference proceedings in the retrieved research documents (see Fig. 1).

2.4. Data selection

2.4.1. Search techniques

A systematic review approach necessitates a thorough examination and evaluation of all existing literature. Fig. 2 outlines the steps involved in this protocol. Four electronic databases were systematically searched, yielding a set of results. Through a process of filtering, redundant research papers were removed, resulting in a final curated list of 754 papers. The titles of these papers were further reviewed to eliminate duplication, resulting in a shorter list of 365 articles. These selected papers underwent quality assessment based on predefined criteria, leading to the identification of 157 papers that aligned well with the research questions. The flowchart utilized in this study adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines, illustrating processes of constructing a comprehensive database for both quantitative and qualitative analysis, as depicted in Fig. 2.

2.4.2. Scrutiny and sorting procedure

The initial list of 754 findings as depicted in Fig. 2 underwent a thorough filtering and examination process, involving several steps. Firstly, establishing the relevancy of the titles, the abstracts were quickly skimmed. Their alignment with the research questions. Additionally, specific criteria were applied, including the requirement for articles to be written in English and to pertain to conference proceedings and journal articles. In cases where multiple versions of the same article were identified, only the most recent and up-to-date version was included. As summarize below in Table 2, the systematic literature review (SLR) focused on articles published between January 1, 2002, and December 25, 2022.

2.5. Data extraction

2.5.1. Assessment of quality research

By employing a rating system, we implemented a process to narrow down the original study. Each article was assessed and assigned a score based on its ability to address specific queries. The allocation of scores was carried out meticulously, considering the responses that aligned with the analytical questions posed. The guidelines outlined in references [29,31] were utilized as a framework. The rating system employed a scale where "Yes" was assigned a value of 1 and "Partially" was assigned a value of 0.5.

2.6. Data execution

2.6.1. Synthesis data

The last stage of our study involved categorizing the articles as a measure to enhance the reliability and ensure consistency in our revised list. Subsequently, the eligibility criteria outlined were applied to evaluate the database. Both quantitative (numerical outputs) and qualitative information were assessed using criteria that identified the strengths and weaknesses of the findings.

Verification of the reference bibliography can be achieved through specific identifiers, including the research identification number, year of publication, title, and source. The form of research may vary depending on the journal or conference proceedings. The research methodology focused on various aspects such as conventional recycling, semi-recycling, and direct recycling of aluminium, as well as reviews and experiments pertaining to aluminium characteristics. Data analysis encompassed both quantitative and qualitative approaches, while limitations were considered as constraints within the research.

2.7. Results of bibliometric analysis articles

The creation of maps using VOSviewer involved the selection of keywords as the objects of interest, which could represent articles or scholars, as depicted in Fig. 3. Each map typically focused on a single type of item, and in this study, only keywords were considered. The relationships between items on the map were determined by link numbers, indicating the association or connection between them. Link strength, a positive value, represented the strength of the relationship, which was determined based on the number of publications where two words appeared together. By combining items and links, a network was formed.

To evaluate the frequency of keywords, the VOSviewer tool utilized the "complete count" methodology. Keywords that appeared three or more times were considered, resulting in a total of 77 eligible words that met the threshold, with a minimum occurrence of four. These frequent keywords were then used to create a mapping network, consisting of 77 interconnected nodes grouped into six fuzzy clusters. The cluster nodes

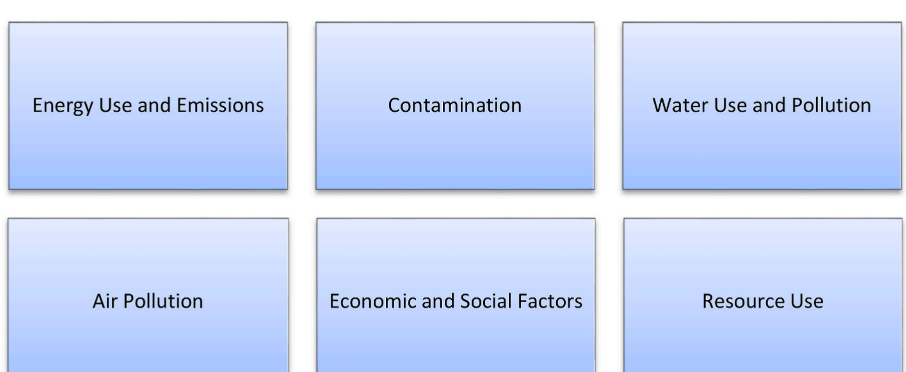

Fig. 1. Environmental aluminium recycling challenges [12].

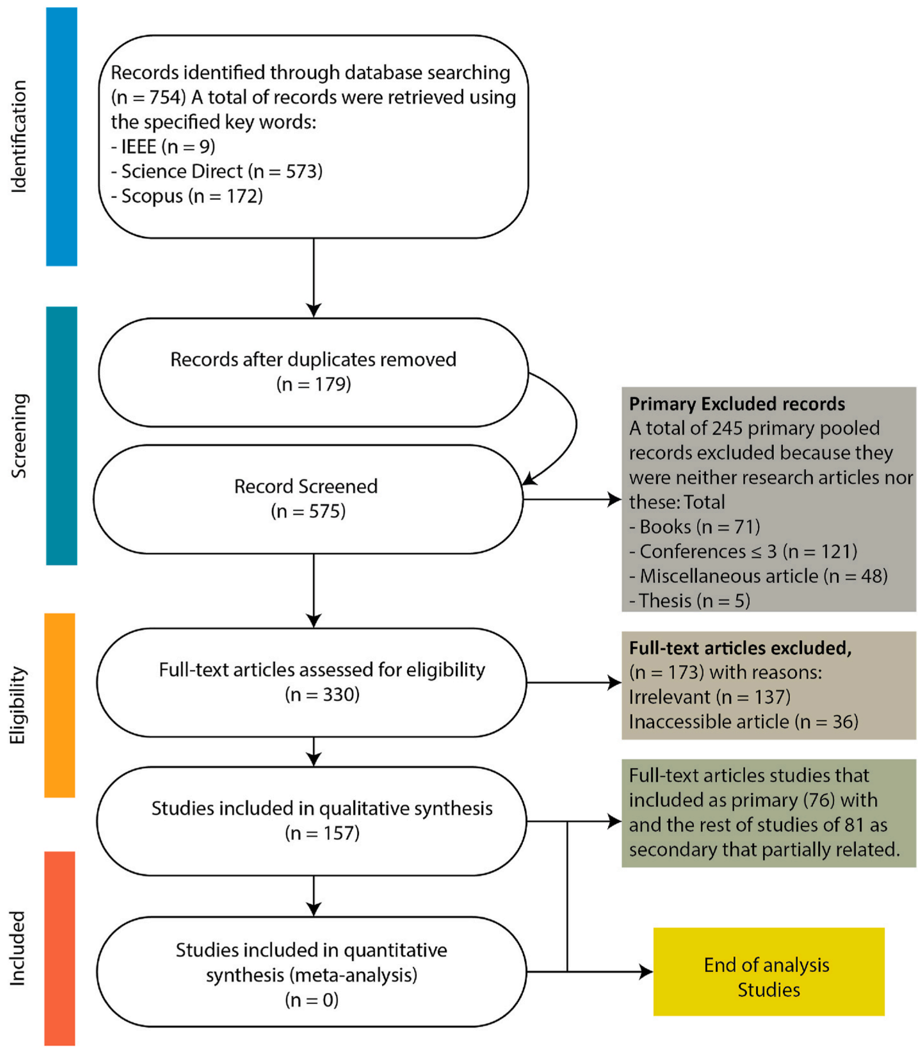

Fig. 2. A flowchart demonstrating PRISMA's methodology.

Table 2
The included criteria and excluded criteria.

Included Criteria	Excluded Criteria
A. Paper written in English	Any other language papers.
B. All papers discussing in Sustainable manufacturing, Direct metal recycling; Powder metallurgy; Hot extrusion; Hot forging; Cold forging; Life cycle assessment	Papers that had no relationship to the research questions.
C. Matching papers published between January 1, 2002 and December 15, 2022.	The gray research articles; papers of no relevance to survey questions or inaccurate journals, excluding Sustainable manufacturing, Direct metal recycling; Powder metallurgy.
D. Articles that will possibly resolve at least one research question	
E. Research Question 3 (RQ3), it included mainly empirical studies that investigated the variables related to Sustainable manufacturing, Direct metal recycling; Powder metallurgy; Hot extrusion; Hot forging; Cold forging; Life cycle assessment.	Any obsolete papers with the same author that tended to repeat this information. The text of articles that cannot be accessed through search engine results or by the writers themselves cannot be found.
F. Papers (≥3 pages)	Short papers (<3 pages)

represented keywords that were frequently used together, indicating their connection and recurring presence in the analyzed publications.

There are six clusters that intend to discuss aluminium alloy. The first cluster with red nodes contains six items: aluminium alloy, aluminium, corrosion, perception, solidification, and sustainability, with occurrence rates of 8,30,6,5,5, and 16, respectively. Demonstrate the aluminium life cycle to assist in the decision-making strategy of recycling aluminium to ensure sustainability.

The second cluster of green nodes has mostly (5 items) that intend to link with aluminium alloy, mechanical properties, micro structure, solid state recycling, and sustainable manufacturing, with occurrences of 7, 15, 16, 6, and 6.

The third cluster with blue nodes has four items that aim to demonstrate density, hardness, stir casting, and waste recycle with occurrences of 6, 8, 5, and 5 respectively. As a consequence, the fourth cluster is described in four items: carbon footprint, energy efficiency, waiver material impact, and life cycle assessment, with occurrences of 6, 5, 6, and 39. While the decision-making strategy with aluminium life cycle assessment. The fifth cluster contains four purple nodes: aluminium dross, material flow analysis, recycling, and waste management, with occurrences of 5, 7, 64, and 9, respectively. However, the strategy for recycling aluminium with additive manufacturing. The sixth cluster contains two items: circular economy and packaging, with 22 and 6 occurrences, respectively. The packaging material decision-making strategy.

3. Recycling techniques of aluminium

The economic benefits of recycling aluminium alloys have been

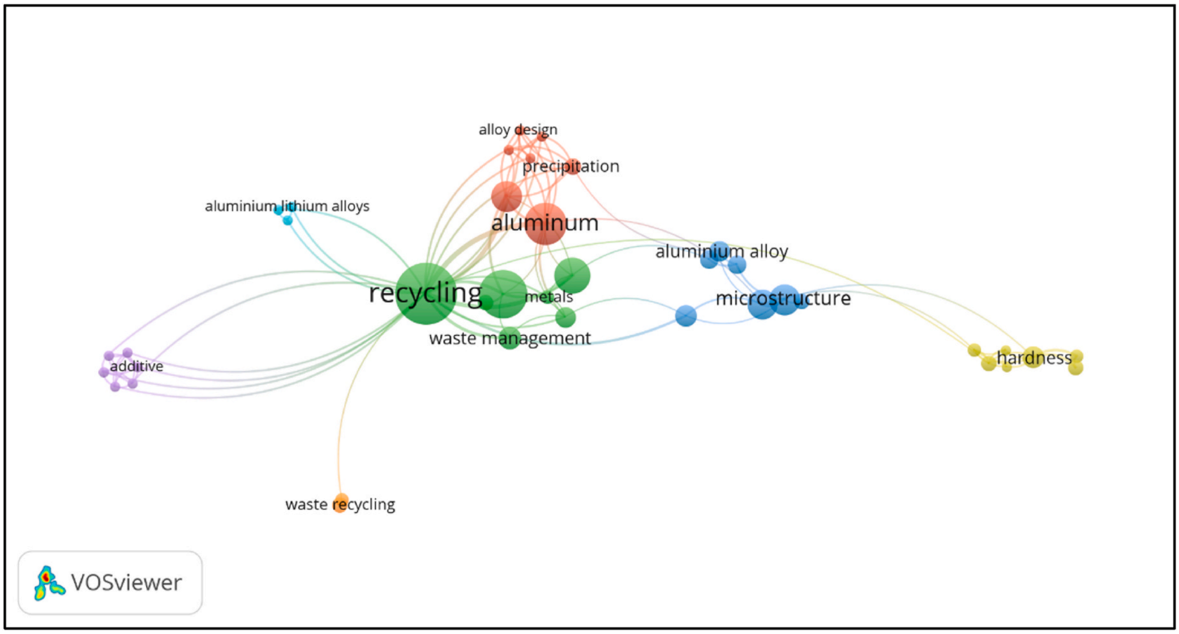

Fig. 3. Mapping of co-occurrence keywords in VOSviewer.

demonstrated, leading the aluminium industry to focus on developing and implementing technologies that maximize these benefits. There are three primary techniques for recycling aluminium: conventional recycling (CR), semi-direct recycling (SDR), and direct recycling (DR). Fig. 4 provides a comparison of the fundamental steps involved in each recycling technique. The classification of these techniques was based on the number of steps and processes they entail.

In conventional recycling, which is commonly practiced in many industries, aluminium is melted at temperatures exceeding its melting point to produce a secondary ingot. The composition of the alloys is

Fig. 4. A comparison of conventional, semi-direct recycling and direct recycling techniques for aluminium alloy chips.

controlled to match standardized grades. This approach is referred to as conventional recycling in this paper. Semi-direct recycling (SDR) involves a mandatory pre-processing step prior to the main recycling process. Fig. 4 (B) illustrates the three main forming processes in SDR: powder metallurgy, hot extrusion, and spark plasma sintering. Each of these processes requires specific pre-processing steps such as ball milling and cold pre-compaction. On the other hand, direct recycling (DR) is a one-step process that directly produces a final product without the need for pre-processing. Currently, there are only three processes recognized as DR techniques: cold forging, hot forging, and compressive torsion.

3.1. Aluminium recycling practices

3.1.1. Conventional recycling

In the majority of industries, the current practice of recycling aluminium involves utilizing a melting technique to create a secondary ingot. This process includes controlling the composition of alloys to meet standardized grades. Refiners and remelters play crucial roles in the aluminium recycling process by establishing connections with collectors, dismantlers, metal merchants, and scrap processors who are responsible for the collection and treatment of scrap materials. Aluminium recycling utilizes scrap aluminium as its raw material. Once the scrap is collected, it undergoes sorting and cleaning procedures before being used in metal production. The scrap is then introduced into melting furnaces where it is melted to transform the metal into a liquid state. Subsequently, the liquid metal is purified, adjusted to the desired alloy composition, and shaped into a form suitable for processing and fabrication. Rotary and electric furnaces are commonly employed for melting scrap aluminium. Fig. 5 presents a process diagram summarizing the general structure of secondary aluminium production using secondary raw materials [32].

Before the melting process, it is crucial to prepare the aluminium chips by cleaning, drying, and compacting them. In conventional practices, remelters typically use a degreasing fluid to clean the finely machined chips, followed by a heating step to eliminate moisture. Unfortunately, this process often leads to the formation of new oxide films. Losses occur at different stages of the recycling process. For instance, there are losses due to metal oxidation during the melting phase, losses caused by mixing with slag on the melt surface, and scraps generated during the casting and subsequent processing of the aluminium ingots [24].

3.1.2. Semi direct recycling

Instead of relying on conventional recycling (CR) techniques that

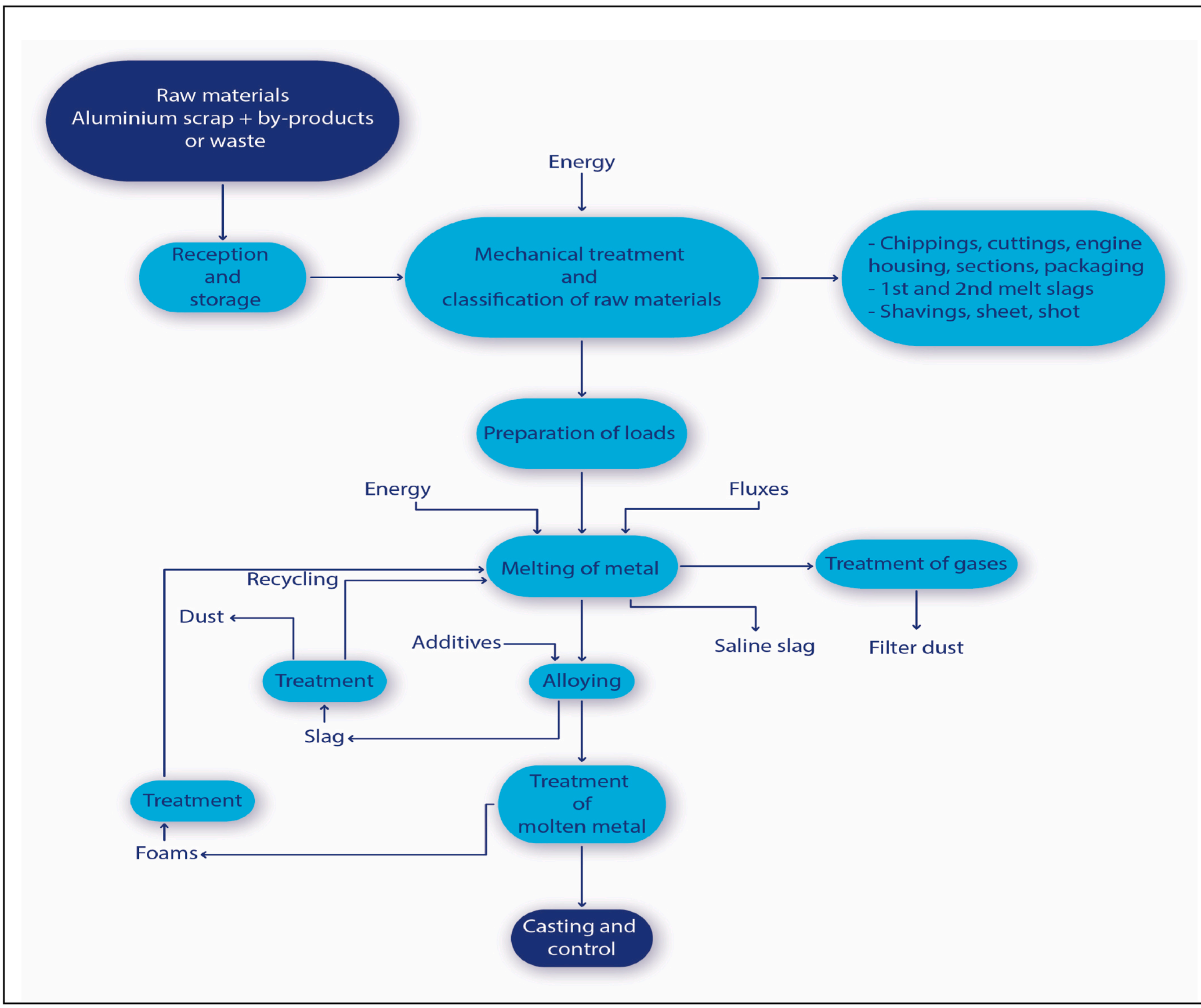

Fig. 5. Process diagram of secondary aluminium production [32].

utilize extremely high temperatures to reach the melting point, it is more favorable to recycle wrought aluminium alloys using semi-direct recycling (SDR) methods. Previous studies have highlighted the significant energy consumption associated with conventional aluminium recycling and subsequent refinement. SDR is characterized as a partially direct recycling process that involves additional steps before the recycling process is completed. The SDR approach encompasses three techniques: powder metallurgy, extrusion, and spark plasma sintering, all of which operate under solid-state conditions and offer notable energy savings. Both powder metallurgy and extrusion techniques require supplementary steps to complete the recycling process. In powder metallurgy, aluminium chip scraps are ground using ball mills before undergoing cold compaction, while hot extrusion techniques involve ball mills, preheating, and cold compaction to produce cold billets. Spark plasma sintering also requires cold compaction to produce billets.

3.1.2.1. Technique of powder metallurgy. Powder metallurgy (PM) is a manufacturing technique where powdered materials are mixed together, shaped into a desired form through compaction, and then subjected to sintering in a controlled environment to facilitate bonding. The PM process typically comprises four main steps: powder manufacturing, powder blending, compacting, and sintering, as shown the general flow of PM processing in Fig. 6. Compacting is typically done at room temperature, while sintering is carried out at high temperatures and atmospheric pressure [33]. This process is highly regarded for its ability to produce near-net-shaped products with properties comparable to conventionally produced items, often requiring minimal or no secondary machining, and enabling increased mass production rates [34].

Powder metallurgy is widely employed in the manufacturing of various components utilized in automobiles, aircraft, spacecraft, nuclear reactors, computers, and household appliances. It stands out as a flexible and versatile manufacturing technique due to its capability to process different types of materials. This enables the production of porous products with uniform porosity, as well as materials with specific electric and magnetic properties achieved by combining different materials. For instance, it facilitates the processing of refractory metals with high melting points, which can be difficult to handle using conventional techniques. It also enables the production of hard metals for cutting tools, frictional materials, and dispersion-strengthening materials such as aluminium combined with alumina particles to enhance strength [35].

In contrast, certain articles have highlighted powder metallurgy as a viable technique for aluminium recycling. They have specifically focused on the common method of breaking down metals prior to manufacturing processes, which produces a substantial amount of chips of wasted aluminium [36–40].

The article presents the outcome of research that enables the problem of processing secondary waste from expensive aluminium alloys without irreversible metal loss to be solved [41]. Hence, the dry sliding wear behaviour of a powder metallurgy-fabricated recycled aluminium AA6061-based MMC reinforced with graphite particles and heat treated addressed by Ref. [42]. Powder metallurgy has significant advantages over melting, including lower processing temperatures when compared to the melting process in traditional methods.

3.1.2.2. Extrusion procedure. Hot extrusion is a novel method that provides a more efficient way of utilizing primary materials and reducing the number of process steps required. It involves combining hot profile extrusion with subsequent machining or turning, as well as hot extrusion of the generated machining chips, to produce semi-finished parts. The concept of this technique was introduced and patented by Stern in 1945 [43]. The effectiveness of hot extrusion is made possible by applying high pressure, high strain, and a temperature just below the melting point, enabling the joining of aluminium. The strain helps crack

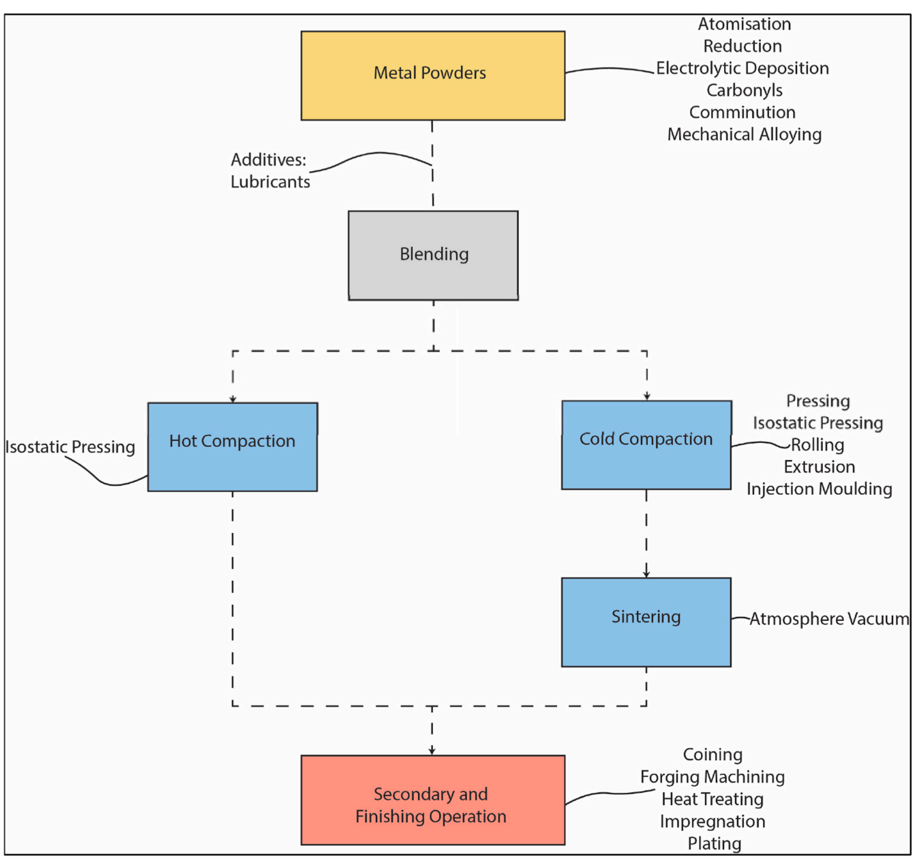

Fig. 6. General flow sheet of powder metallurgy processing [33].

the oxide layer, while the combination of pressure and temperature facilitates the joining process by contacting the pure aluminium surface. Compared to conventional process chains, this approach requires a significantly smaller amount of energy, utilizing only 5–6 GJ/ton, which accounts for approximately 5–6% of the energy required by traditional methods. During the semi-direct conversion of aluminium chips into compact metal through extrusion, there is a waste of around 2 % due to the presence of impurities that cannot be removed, and the extrusion waste can reach up to 3 %. However, the process achieves a recovery rate of 95 % for the aluminium chips [26]. Alternative recycling methods involve converting chips into powder using ball milling. In this study, a novel technique was utilized, which directly recycles the material from the chips through cold or hot forging, followed by hot extrusion. By eliminating the need for ball milling, this approach provides a more economically efficient recycling process. The recycling of aluminium alloy AA6061 provides benefits in terms of energy conservation and the preservation of natural resources, as discussed in previous works [1,37,44–48]. This innovative method can also be utilized for recycling chips obtained from aluminium matrix composites, which pose even greater difficulties when processed using alternative techniques.

The recycling process of aluminium chips as a secondary resource is depicted in Fig. 7. The extrusion process is influenced by several factors, including the optimal ram speed, preheat temperature, and preheat time [49]. Pantke et al. [50] have found that recycled aluminium chips of varying sizes and shapes can be obtained by adjusting the cutting depths during chip production. Higher cutting depths during rough machining necessitate lower cutting depths during finishing processes. The stability of the billets' structure is influenced by the geometry of the chips and the parameters employed during the compacting process, which promote the interlocking of the chips. However, these factors do not have a significant impact on the mechanical properties of the extruded profiles. The hardness of each profile is comparable, and there are no significant differences based on the particular raw material used.

3.1.2.3. Sintering among spark plasma. Spark plasma sintering (SPS) is a novel technique employed in semi-direct recycling (SDR) of aluminium. It involves a pre-process of cold pressing and the main process of SPS to consolidate and recycle aluminium chips. One distinctive feature of SPS is the direct passage of pulsed DC current through the graphite die and the compacted chip, as illustrated in Fig. 8. This dynamic compaction of scrap, combined with joule heating from the electric current, results in the partial fracture of stable surface oxides, desorption of trapped gases, and activation of metallic surfaces addressed by Paraskevas et al. [52]. These effects promote efficient solid-state welding of the chips and eliminate residual porosity. The heat generation in SPS is internal,

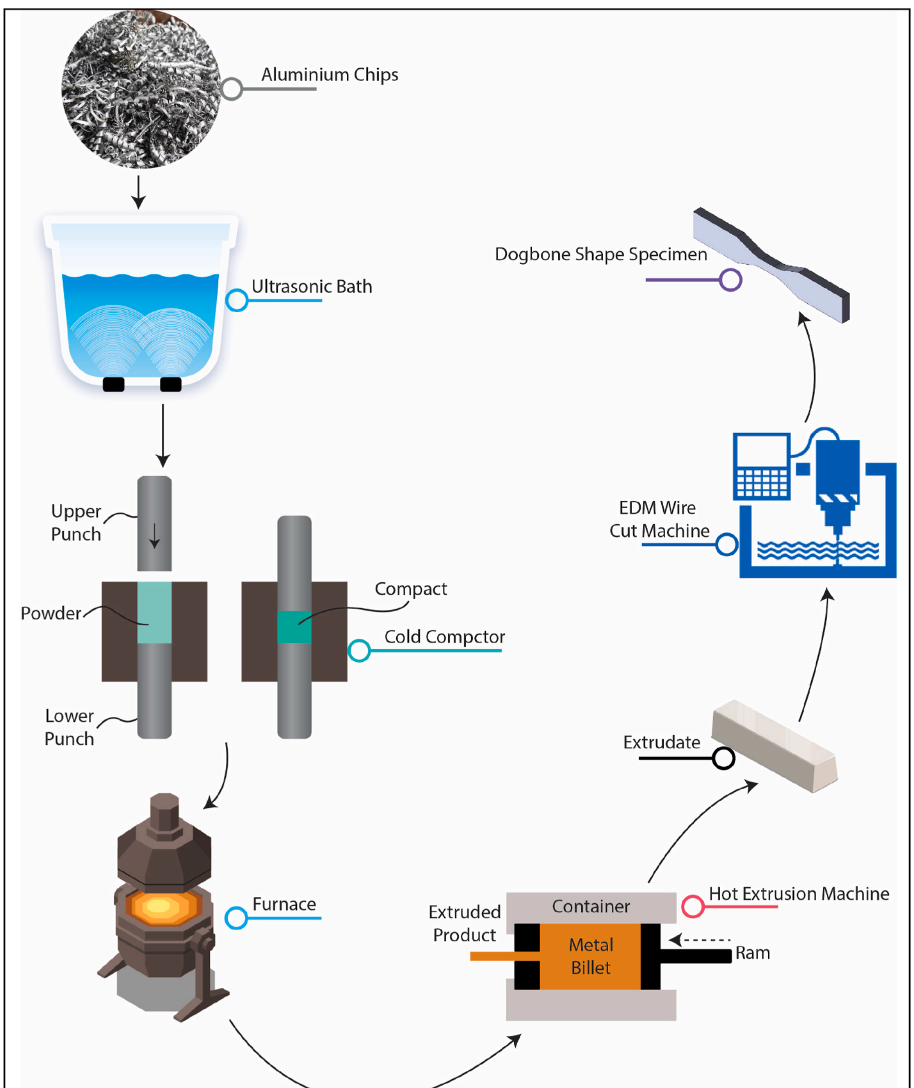

Fig. 7. Recycling aluminium chip flow process as a secondary resource [51].

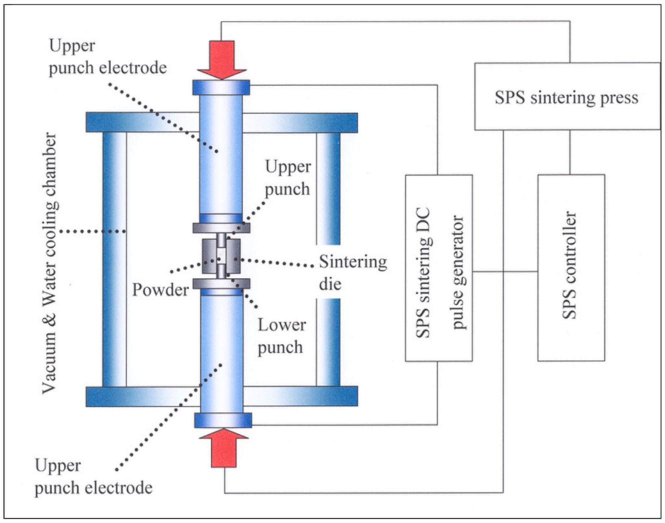

Fig. 8. Spark plasma sintering schematic [54].

unlike conventional hot pressing that relies on external heating elements. This characteristic enables a rapid heating rate, making the sintering process generally fast. In one study, the influence of metal and nickel on the mechanical properties and thermal stability of alloys at low and high temperatures was investigated. By utilizing the technique of melt spinning, Al–Si–Fe-X alloys were rapidly solidified into ribbons, which were subsequently ground into powder using a planetary ball mill. The resulting powder material was then compacted using spark plasma sintering [53].

Unlike conventional hot pressing, where external heating elements provide the heat, spark plasma sintering (SPS) generates internal heat. This internal heat generation enables a significantly high heating rate and results in a generally fast sintering process. SPS technology offers the advantage of producing near-net-shape parts or multiple parts in a single cycle, providing flexibility in production. Industrial-scale SPS systems are already available, and ongoing development includes a field-activated/assisted sintering (FAST) system. The FAST system aims to efficiently produce near-net-shaped products with a cycle time of less than 1 min [55]. These recent advancements in the field contribute to the progress of industrial implementation, scaling-up, and the overall value of the proposed approach.

3.1.3. Direct recycling

Direct recycling (DR) is a novel process that allows for improved utilization of primary materials and a decrease in the number of process steps compared to traditional methods. This approach reduces the energy required for remelting scraps in order to create new billets. Unlike other recycling processes, direct recycling does not involve transforming the material from chips into powder. Instead, it involves directly recycling the material from industrial machining waste through either cold or hot forging (also known as cold or hot pressing). This method of aluminium and alloy recycling is relatively straightforward, consumes minimal energy, and has a positive environmental impact.

Currently, there are three distinct types of DR techniques available for aluminium recycling. The classification of these techniques often depends on the temperature at which the recycling process takes place since metal deformation can occur in either the hot or cold mode. Cold forging is performed at room temperature, while hot forging and compressive torsion techniques involve plastic deformation of the metal at elevated temperatures and strain rates, resulting in simultaneous recrystallization and deformation.

3.1.3.1. Compression torsion process. The compressive torsion process (CTP) involves the simultaneous application of compressive and shear loadings to cylindrical specimens. In this process, a cylindrical specimen is placed within a container, and the upper and lower dies move vertically to apply a compressive load while also revolving in opposite directions to apply a torsional load. This process, depicted in Fig. 9, differs from high-pressure torsion as it utilizes significantly lower pressure (several hundred MPa) and can subject a bulk cylindrical specimen, rather than just a thin disc, to severe deformation. The compressive torsion process (CTP) offers a significant advantage by allowing severe plastic deformation of materials without altering the original specimen shape [56]. This process enables the direct conversion of metal chips into the desired end product [57,58]. In CTP, cylindrical metal specimens experience substantial shear strain through rotational loading while simultaneously undergoing compressive loading, all without changing their cylindrical shape. Since shear loading occurs under hydrostatic compressive conditions, CTP can be applied not only to bulk metals but also to non-continuous forms such as powders or chips. When applied to bulk metals, CTP can lead to improved mechanical properties through the refinement of the microstructure [59]. In contrast, when applied to powders and chips, the compressive torsion process allows for easy and efficient consolidation at low temperatures, resulting in dense and compacted materials [60].

3.1.3.2. Screw extrusion. The screw extrusion of aluminium is an innovative continuous solid-state process that has been developed collaboratively by the Norwegian University of Science and Technology (NTNU) and Norsk Hydro [61]. The research project received funding from the Norwegian University of Science and Technology (NTNU). As part of the study, the AA1370 aluminium alloy was processed at a temperature of 450 °C using an innovative metal screw extrusion technique [62]. Fig. 10 illustrates the structure of a screw extruder. Within a container, a screw is rotated by a motor. Granulated material is fed into the machine through a rear feed hole. The material enters the gap between the screw and the container and is pushed forward by the rotating screw. As the material makes contact with the heated container walls and undergoes deformation, it gets heated. The extrusion chamber at the front end of the screw gets filled, resulting in the consolidation of the granulate through the combined effects of high pressure, elevated temperature, and the deformation caused by the rotating screw. Comparisons were made between literature data on pure and diluted alloys to establish a correlation between strength and electrical conductivity for wires produced through cold drawing and screw extrusion. Despite exhibiting relatively low strength, the wires produced through screw extrusion showed superior electrical conductivity compared to other alloys, as discussed in the referenced work [62]. Ultimately, the compacted aluminium material is continuously extruded through the die opening, resulting in the formation of a profile.

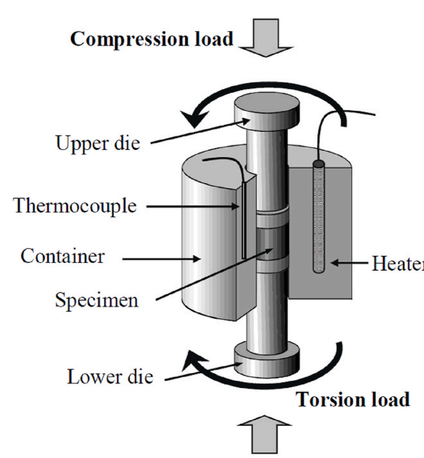

Fig. 9. Compressive torsion process schematic [57].

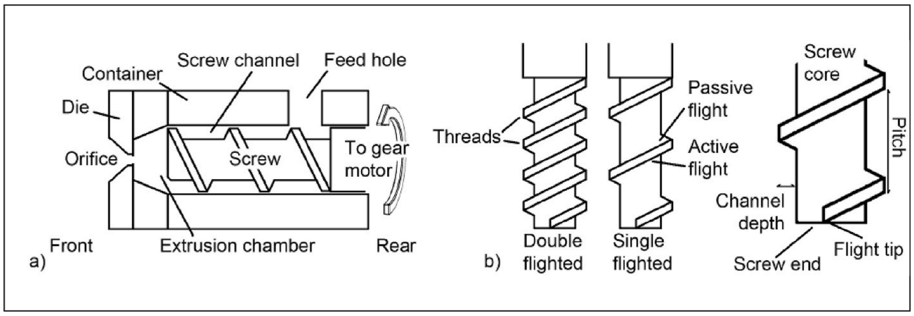

Fig. 10. a) Schematic drawings of a screw extruder. b) Geometry of single and double flight screws [63].

3.1.3.3. Hot forging. This section introduces a new DR approach using hot forging that reduces the number of steps, requires less energy and has important operating cost benefits. Hot forging requires plastic deformation to occur; therefore, a high work piece temperature, which matches the metal's recrystallization temperature, must be attained throughout the process. This technique utilizes a single process in which the chip is directly pressed under specific temperature conditions, which is shown in Fig. 11. Some authors intend to discuss the hot forging fulfilment in sustainable, optimisation, and life cycle assessment [47, 64–68].

In general, forging refers to a process known as hot forging, where the temperature is raised above the recrystallization point [69]. When a heated object is forged, it becomes more malleable since there is no strain-hardening during the deformation of the metal. This results in a reduction in energy demand and simplifies the metalworking process by enhancing the malleability of the metallic alloys and reducing strength of working material. As a result, it eliminates strain hardening and enables increased deformation with lower energy requirements during high-temperature metalworking operations [70]. In industrial settings, two main types of hot forging techniques are widely employed: open-die forging and closed-die forging. Closed dies are essential for achieving precise forging of parts without any burrs. A recent discovery by Doege and Bohnsack [71] introduced a new closing device that significantly reduces the energy required for closing and minimizes the pressing load. Consequently, these advancements in closing techniques have the potential to improve recycling processes.

3.1.3.4. Cold forging. Cold forging, also known as cold pressing, involves the insertion of a chip into a die and its compression using a second closed die. In this particular study, researchers at the University of Texas A&M in the United States examined the deformation of aluminium (A6061) rings using different types of palm oils and their derivatives. The investigation focused on the utilization of palm oil-based biolubricants in the cold-forging process for aluminium alloy 6061. The study serves as a case study, simulating and highlighting the application of various palm oil variants in this process [73,74]. The deformation occurs at room temperature and results in the transformation of the initial part's shape and size to match that of the die, as depicted in Fig. 12. Cold forging is often highly automated, enabling cost-effective production of parts. Additionally, this process offers the advantage of preventing grain growth, resulting in metal grains that align perfectly with the part's shape, enhancing strength and surface

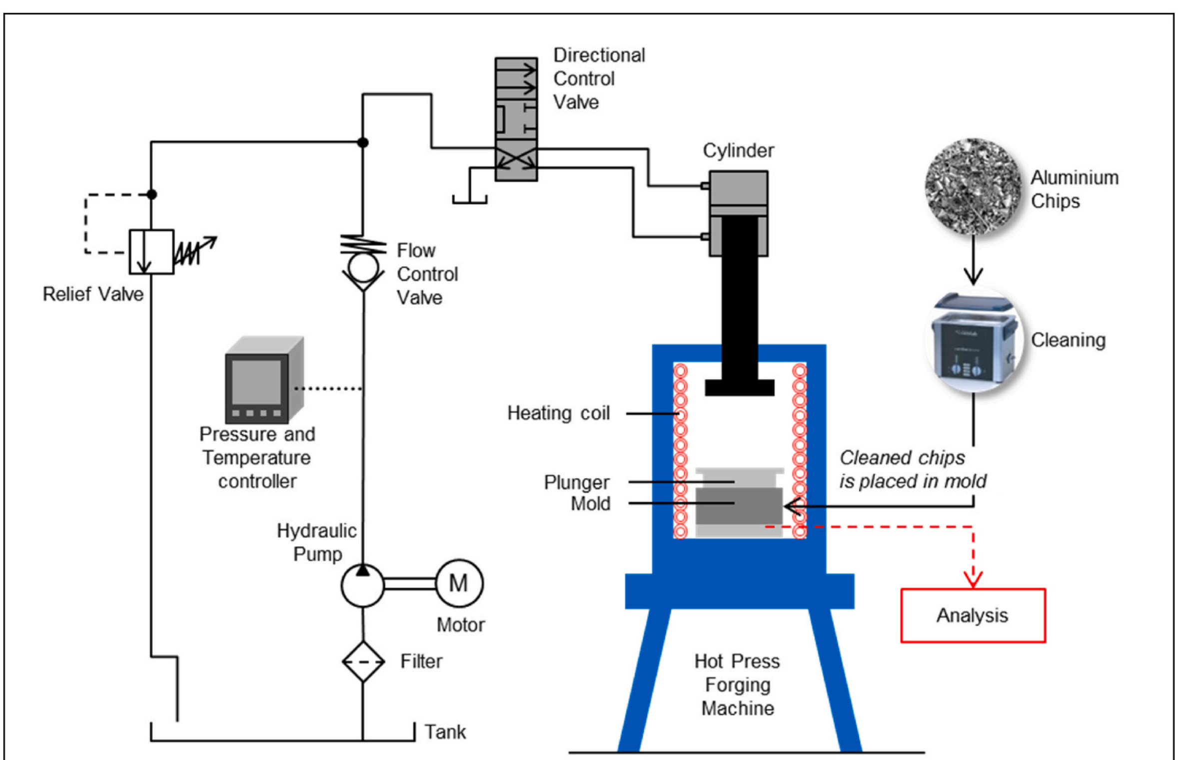

Fig. 11. Hot forging schematic [72].

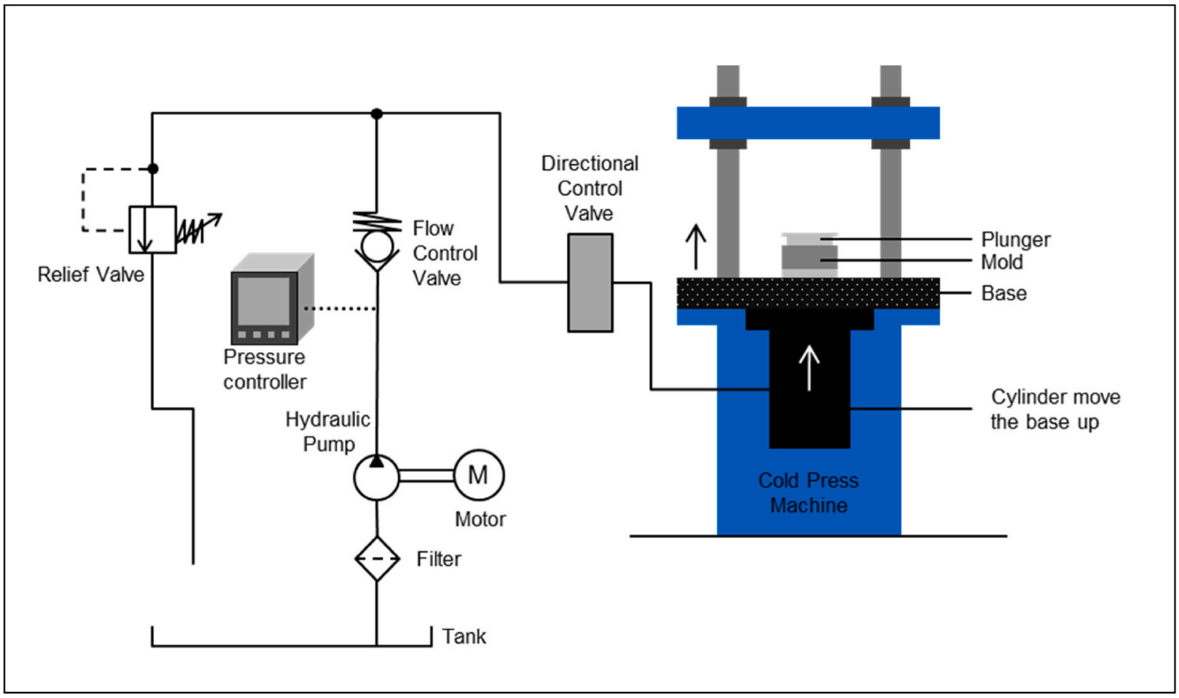

Fig. 12. Cold press schematic [72].

resistance. The relatively straightforward nature of the process contributes to material savings and emphasizes high precision, close tolerances, and improved surface finishes without requiring excessive finishing steps.

3.2. Discussion

Table 3 and Fig. 13 summarize all published work on recycling aluminium according to the techniques, year of publication, the process involved and the number of steps. There have been 16 publications regarding aluminium recycling via conventional techniques that require melting as the main process. Beginning in 2005, several authors have improved upon previous work by combining the melting process with other secondary processes, such as hot extrusion [75], cold forging [76] and ball milling pre-process [77]. As for the SDR technique, more than two steps are included within the process. The most commonly used pre-process step is cold forging [78,79].

Hot extrusion is the most preferred SDR technique because it has been consistently studied from 1996 to 2022 (42 publications). Only six publications, i.e., Aizawa et al. [95], Samuel [20], Fuziana et al. [48], Enginsoy et al. [38], Rojas-Díaz et al. [39] and Sidelnikov, S et al. [41], have discussed a powder metallurgy process for the SDR of aluminium, while four publications have discussed cold forging with sintering [73,74,104,106]. Additionally, the three new studied of SDR through spark plasma sintering (SPS) addressed by Paraskevas et al. [52], Guillon, Olivier et al. [55], and Andrea Školáková et al. [53]. On contrary, the research focused on direct recycling which has (24 publications) and started from 2007 to 2022. The newly developed technique for the DR of aluminium, which has only a single step in its process, was introduced in 2007 by Tahara, utilizing compressive torsion processing (CTP). Studied on DR proceeded by Kuzman et al. [121], who utilized cold forging and followed by Widerø and Welo [122], using screw extrusion. This technique was further explored using the hot forging process by Lajis et al. [123], Yusuf et al. [27], Khamis et al. [67], Shahrom et al. [124], and Ruhaizat et al. [68]. This alternative technique has only been discussed in twenty four publications. There are only twelve publications that have employed heat treatment as a post-processing.

Fig. 14 illustrates the statistical analysis of the publications analyzed in the literature over a period of time. Starting before 1995, authors have initiated studies regarding the recycling of aluminium using the conventional process based on melting. This technique has been continuously studied by enhancing the melting process via furnace upgrades and the addition of secondary pre- or post-processes. For example, Puga et al. [86] found that using induction melting leads to metal recovery rates of up to 90 % and that not using traditional salts and fluxes helps to reduce the generated waste. Velasco and Nino [87] Rotating and reverberatory industrial furnaces were discussed for recycling aluminium alloys, showing that the latter are highly productive and easy to operate with high melting rates, homogeneity, and energy efficiency. However, previous publications have not provided a direct comparison with either the SDR or DR techniques.

SDR techniques originated by Gronostajski et al. [92] utilized fabricated composites of aluminium produced via the hot extrusion process. This process (extrusion) in the SDR category is assumed to be the most favorable process among all aluminium recycling techniques. Evolutionary advancements in the hot extrusion process include the billet preparation method, additional reinforcing phase and die geometry. Fogagnolo et al. [25] used a different pre-process, i.e., the cold and hot forging. The hot forging and extrusion route is an optimal process from a cost benefit ratio perspective. Meanwhile, Gronostajski and Matuszak [93], along with Gronostajski et al., developed a Solid Die Re-forging (SDR) technique for granulated aluminium and its alloy chips. This technique involves transforming these chips into a final product with reinforcing phases, such as aluminium oxide, tungsten, carbon, ferrochromium, and aluminium bronze comminuted chips [19,94]. Studies have demonstrated that the relative densities of the composites produced through hot extrusion are nearly identical (over 98 %) to those of solid materials. The design of the extrusion die also plays a crucial role in ensuring effective bonding between the chips. A well-designed die facilitates an extrusion process that ensures adequate billet densification and chip bonding. A study showed that Equal Channel Angular Pressing (ECAP), which was implemented by Cui and Roven [99] and Cui et al. [102] is an alternative die geometry that introduces higher imposed strains and higher pressures on the recycled chip, resulting in no voids in the produced extrudates. Therefore, SDR can be described as the best technique because the recycled aluminium

Table 3
Publications on aluminium recycling processes.

References	Year	Pre-process			Main process								Post-process	Step Number
		Milling/Mixing	Cold Press	Sintering	Melting	Cold Press	Sintering	Hot Forging	Cold Extrusion	Hot Extrusion	Compressive Torsion	Rolling	Heat Treatment	
Conventional Recycling														
[80]	1983				●									1
[81]	1986				●									1
[82]	1994				●									1
[83]	1997				●									1
[84]	1998				●								●	2
[75]	2005				●					●				2
[85]	2005				●									1
[76]	2009		●		●									2
[86]	2009				●									1
[87]	2011				●									1
[77]	2013	●			●									2
[88]	2017				●					●	●			3
[89]	2019	●			●									2
[56]	2019	●			●						●			3
[90]	2020	●												1
[91]	2021	●			●									2
Semi Direct Recycling														
[92]	1996		●							●			●	2
[24]	1997	●	●							●			●	3
[93]	1999	●	●							●				3
[78]	2000	●	●							●				3
[19]	2000	●	●							●				3
[94]	2001	●	●	●						●				4
[95]	2002	●	●				●	●						4
[25]	2003		●					●		●				3
[20]	2003	●				●	●							3
[96]	2004									●		●		2
[22]	2005		●							●			●	2
[97]	2009		●							●				2
[98]	2009	●	●							●				3
[26]	2009		●							●				2
[99]	2010		●							●				2
[100]	2011		●							●				2
[101]	2012		●							●				2
[102]	2011		●							●				2
[103]	2011		●						●			●		3
[43]	2012		●							●				2
[43]	2012		●							●				2
[50]	2013		●							●				2
[104]	2013					●	●							2
[52]	2014		●				●						●	2
[48]	2014	●				●	●							3
[105]	2014		●						●	●				3
[106]	2014					●	●							2
[107]	2015		●	●					●	●				4
[79]	2015		●							●				2
[108]	2016	●	●							●				3
[109]	2016		●				●							2
[110]	2016	●	●				●							3
[111]	2016		●							●				2

(*continued on next page*)

Table 3 (*continued*)

References	Year	Pre-process			Main process								Post-process	Step Number
		Milling/Mixing	Cold Press	Sintering	Melting	Cold Press	Sintering	Hot Forging	Cold Extrusion	Hot Extrusion	Compressive Torsion	Rolling	Heat Treatment	
[112]	2017		●							●				2
[113]	2017		●							●				2
[114]	2017		●							●				2
[115]	2019	●								●			●	3
[116]	2020	●			●									2
[117]	2021	●								●				2
[118]	2022	●			●						●		●	3
[119]	2022	●								●				2
[41]	2023		●							●		●	●	3
Direct Recycling														
[59]	2007										●			1
[63]	2011									●				1
[120]	2012									●				1
[121]	2012					●								1
[120]	2012					●								1
[122]	2013									●				1
[1]	2013							●						1
[123]	2013							●						1
[27]	2013							●						1
[47]	2014							●						1
[106]	2014							●						1
[124]	2014							●						1
[125]	2014										●			1
[57]	2014										●			1
[126]	2015					●								1
[67]	2015	●						●						2
[127]	2017					●								1
[128]	2018	●								●				2
[129]	2019									●			●	2
[130]	2021	●							●					2
[131]	2021	●			●			●					●	4
[68]	2021				●			●						2
[44]	2022				●					●			●	3
[118]	2022	●			●								●	3

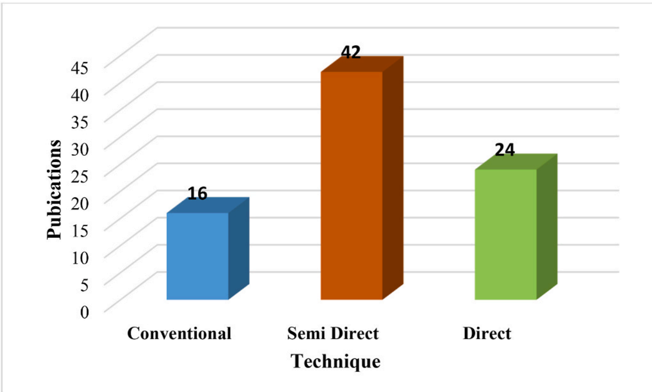

Fig. 13. Number of publications according to the implemented techniques.

exhibits similar mechanical and microstructural properties as conventional cast billet.

Meanwhile, Direct Recycling (DR) is a recently developed alternative approach to aluminium recycling that was discussed by Refs. [19,24,37,44,67,106,118,128–132]. This approach was first executed by Kuzman et al. [121] and Pepelnjak and Kuzman [120] using cold forging. Despite the high relative density and compactness of compressed billets, there are still concerns regarding the quality of the bond between the chips. Lajis et al. [123] and Yusuf et al. [27] extended the work of Kuzman et al. [121] and Pepelnjak and Kuzman [120] by utilizing hot forging for different-sized aluminium chips, demonstrating a remarkable potential in their strength properties and proving that this technique is an acceptable alternative recycling method. Further research on DR is highly recommended to fill knowledge gaps and understand future trends in aluminium recycling. Table 4 and Fig. 15 show the different types of responses in published scientific works on aluminium recycling.

In the existing literature, the key factors that are predominantly considered for analysis are microstructure and tensile tests. Tensile properties provide insights into how a material behaves under tension. Microstructure analysis is crucial for understanding the composition, structure, and deformation characteristics of metals during the recycling process. Tensile tests yield two important strength values: the yield strength (YS), which measures the stress required to induce a specific amount of plastic deformation, and the ultimate tensile strength (UTS), which serves as a universal benchmark for material specification and quality control. The chemical composition is often emphasized in conventional technique publications to ensure the alloy composition aligns with standardized grades. Additionally, other factors considered include oxygen content analyses, tribological tests, as well as assessments of normal and planar anisotropy.

4. Life cycle assessment of aluminium

In this research, a comprehensive review is carried out on nine life cycle analysis (LCA) studies, encompassing sixteen scenarios. These studies employ diverse methodologies to evaluate the environmental impact of aluminium waste management through various approaches, such as recycling (both melting and solid-state methods), incineration, or landfilling. Some intensive studied that support life cycle assessment (LCA) in may vendors such as reviews, case studies, and applications [14,131,138–151]. Therefore, conducting a large-scale international review, the outcome presented a more unbiased analysis of the effects of various waste management strategies systems.

Briefly, the retained studies are those that (1) focused on aluminium with unspecified grade and application; (2) only encompasses studies with comparison of solid waste management systems; (3) includes clear impact assessment category; (4) published in fully English language. Consequently, through a comprehensive international review, a further objective assessment of the environmental impacts associated with various waste management systems was achieved. Fifteen studies were examined in detail, analyzing each major step in the methodological process of goal definition, scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and result interpretation of the life cycle assessment (LCA). The review process followed the methodological guidance provided by Laurent et al. [152], ensuring a more effective application of solid waste management systems. In a recent publication by Dierk Raabe et al. (2022), the topic of “dirty alloys” is discussed, focusing on the impact of impurities present in scrap metal on various aspects such as thermodynamics, kinetics of precipitation reactions, mechanical properties, and electrochemical behavior. The objective of the study is to promote the development and manufacturing of aluminium alloys with maximum utilization of scrap, even including low-quality and diverse types of scrap [153]. According to Tamburini, Elena et al., the focusing aim was on estimating the environmental impacts associated with the production of raw materials and the consumption or refilling of bottles made from polyethylene terephthalate (PET), polylactic acid (PLA), or aluminium. The study also considered the end-of-life options for plastic bottles, including open and closed-loop recycling for PET and composting for PLA, as alternatives to incineration and landfilling [154]. n their work, Andrea and Maurizio have explored

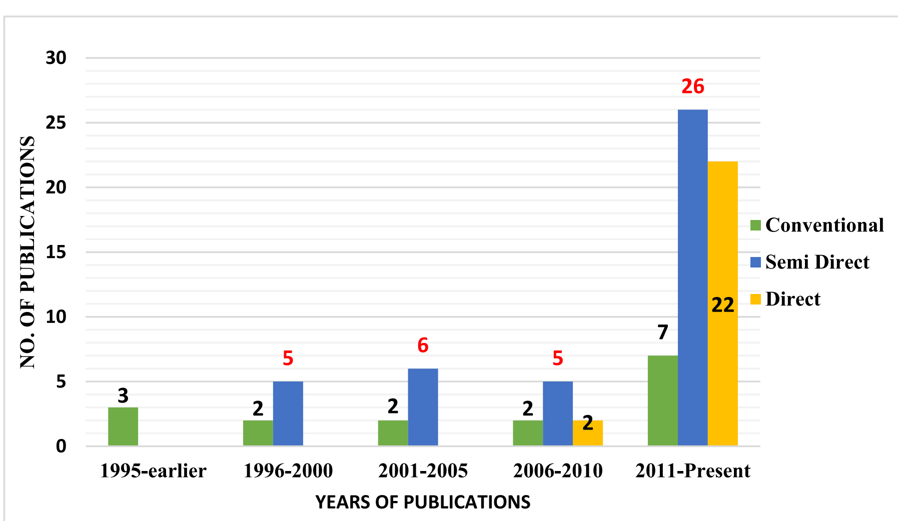

Fig. 14. Historical trend of the examined techniques in the scientific literature.

Table 4
Responses recorded in publications of aluminium recycling.

Year	References & Authors	Tensile	Compression	Density	Microhardness	Microstructure	Fracture	Chem Comp.	Others
1996	[92] J.K Gronotajski et al.	●		●	●				
1997	[127] Sillekens et al.	●			●			●	●
1997	[24] J.K. Gronotajski et al.	●		●	●	●			
1998	[84] Liu and Samuel	●					●		
1999	[93] J.K. Gronotajski et al.	●		●	●	●			
2000	[78] Chmura and Gronostajsk	●	●						●
2000	[19] J. Gronotajski et al.			●				●	●
2001	[94] Gronotajski et al.	●				●			
2002	[95] Aizawa et al.				●	●		●	
2003	[25] Fogagnolo et al.	●				●		●	
2003	[20] Samuel		●	●	●	●			
2004	[96] Y. Chino et al.	●				●			
2005	[75] Geertruydeen					●			
2005	[85] Shinzato and Hypolito		●					●	
2005	[22] K. SUZUKI et al.	●				●			●
2007	[59] Tahara et al.	●				●			
2009	[76] Amini et al.	●					●	●	
2009	[86] Puga et al.					●		●	
2009	[97] Rebhi et al.					●		●	
2009	[98] Sherafat et al.	●		●	●	●			
2009	[26] Tekkaya et al.	●				●			
2010	[99] Cui and Roven.					●			
2011	[100] Güley et al.	●				●			
2011	[63] Widerø and Welo.		●			●			
2011	[87] Velasco and Nino							●	
2011	[103] Chiba et al.	●		●		●			
2011	[102] Cui et al.	●			●	●			
2012	[101] Güley et al.	●							
2012	[43] Misiolek et al.	●			●	●			
2012	[121] Kuzman et al.			●					
2012	[120] Pepelnjak et al.			●					
2012	[133] Widerø and Welo.					●			
2013	[77] David and Kopac					●		●	
2013	[104] Badarulzaman et al.	●			●				
2013	[50] Güley et al.	●			●	●			
2013	[123] Lajis et al.	●				●			
2013	[1] Lajis, Yusuf, & Noh	●				●			
2013	[122] Widerø and Welo					●			
2013	[27] Yusuf et al.	●				●			●
2014	[48] Fuziana et al.			●	●	●			
2014	[105] Haase and Tekkaya	●				●			●
2014	[106] Lajis and Chan	●							
2014	[52] Paraskevas et al.		●	●	●	●		●	●
2014	[57] Kanetake et al.	●				●			
2014	[47] Khamis et al.	●							
2014	[125] Kume et al.	●				●			
2014	[47] Lajis et al.	●							
2014	[124] Shahrom et al.	●							
2015	[134] Chen et al.	●				●	●		
2015	[67] Khamis et al.	●							
2015	[79] Chiba and Yoshimura	●		●		●			
2015	[107] Haase and Tekkaya	●			●	●			
2015	[126] Chan and Lajis	●		●	●				
2016	[108] Mahdi et al.		●		●	●			
2016	[135] Mahdi et al.		●			●			
2016	[109] Mahdi et al.		●		●	●			
2016	[111] Shamsudin et al.	●		●			●		
2017	[112] Rahim and Lajis	●				●	●		
2017	[113] Rahim and Lajis	●					●		
2017	[114] Shamsudin et al.	●							
2017	[127] Lajis et al.	●							
2018	[128] D. Paraskevas et al.	●				●			
2019	[89] E. David and J. Kopac							●	●
2019	[129] M. H.Rady.	●				●			
2019	[56] A. K. Pandey et al.					●			●
2020	[136] K. Abubakar et al.				●		●		●
2021	[137] K. Abubakar et al.				●			●	●
2021	[117] Thomas and Werner	●	●		●				
2021	[130] N. K. Yusuf et al.	●				●			●
2021	[131] N. K. Yusuf.								●
2021	[68] N. E. Ruhaizat et al.	●							
2022	[119] K. DaeHan et al.	●		●					●
2022	[44] S. Al-alimi et al.		●	●		●			
2022	[118] Thomas and Werner			●			●		
2023	[41] S. Sidelnikov et al.							●	●

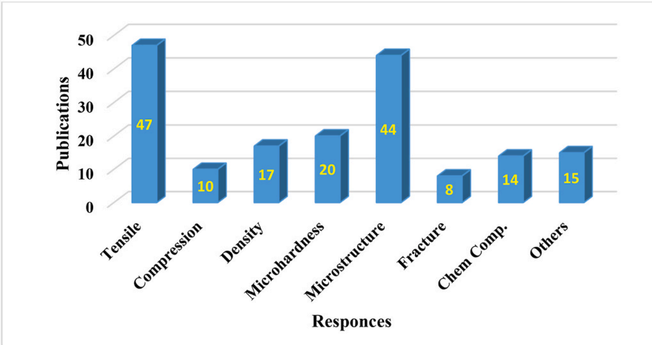

Fig. 15. Graph of the studied responses.

an expanded perspective on the methodology of life cycle assessment (LCA) by incorporating multiscale modeling techniques to generate life cycle inventory data at the early stages of product design. They propose an approach that allows for practical application in predicting properties of nanostructured polymer systems, specifically focusing on the manufacturing of a marine engine cover [155].

Through a comprehensive review of various studies, two distinct classes of functional units (f.u.) have been identified. The first class is unitary f.u., which is explained by a specific measure such as managing 1 tonne of waste. The second class is generation-based f.u., which is explained by waste generation within a defined region and time period. The establishment of system boundaries determines which processes within the life cycle are included or excluded from the assessment [156]. Building on past practices, Laurent et al. [152] have emphasized three specific aspects when defining system boundaries and analyzed each aspect individually. These aspects include capital goods applied in the treatment chain (e.g., construction and decommissioning of facilities and machinery), collection and transportation, and the treatment of secondary products and final residuals that hold value. Furthermore, the authors propose including primary production within the system boundaries, as some studies tend to exclude the process of obtaining virgin aluminium.

Data sources can be categorized into three classes (1) primary data – site-specific data from field investigation (2) database – LCA software-embedded database (3) literature data – from past studies and peer reviewed sources. Impact categories and damage categories in impact assessment were referred to the LCA framework by Jolliet et al. [157, 158].

The final step of life cycle assessment (LCA), known as interpretation, the use of sensitivity analysis to explore the effects of model inputs on the results. This analysis investigates how variations in the inputs affect the outcomes. Additionally, uncertainty propagation is utilized to quantify the overall uncertainty associated with the results. Its purpose is to assess and characterize the level of uncertainty present in the LCA results. Finally, selected environmental preference of waste handling comparison with 3 different scenarios consist of landfill versus recycling (LvR), incineration versus recycling (IvR) and Recycling (melting) versus recycling (solid-state) (R_MvR_S) were discussed in section 4.2.

4.1. Aluminium waste management practices

4.1.1. Landfill

Landfill refers to the controlled and systematic disposal of waste on land, distinguishing it from dumping, which lacks proper management and control. Landfilling results in the release of mixed waste, including methane (CH_4) emissions, carbon dioxide (CO_2) emissions from transportation, and storage. When it comes to aluminium dross, indiscriminate disposal in landfills can pose challenges due to the inert nature of the landfill environment. Over time, chemical reactions may occur during landfill process and closure. Although, aluminium waste sometimes remains inactive in landfills for extended periods, interactions can take place when the buried aluminium comes into contact with alkaline water (pH $\geq$ 9) from various sources [159]. Reactions involving aluminium can lead to the emission of significant quantities of potentially harmful and combustible gases, which are characterized by toxic properties and unpleasant odors.

4.1.2. Incineration

The primary objective of incineration in waste management is to minimize the accumulation of waste that would require disposal in landfills, by transforming it into an inert inorganic ash residue through thermal oxidation. Incineration involves subjecting waste to temperatures exceeding 850 °C [160]. When aluminium undergoes combustion, the carbon present in the waste is largely converted into carbon dioxide (CO_2), resulting in CO_2 emissions. In the case of waste-to-energy (WTE) plants, where combustion is coupled with energy recovery, CO_2 emissions are also generated at production facilities for metals and utilities. The power is generated by a WTE plant displaces the need for power from conventional fossil fuel-based utility power plants. Consequently, the utilization of WTE transfers helps to reduce CO_2 emissions associated with utility power generation.

4.1.3. Recycling

Aluminium possesses the unique characteristic of being recyclable indefinitely without compromising its properties. When aluminium is recycled, it requires only 5 % of the energy compared to the initial extraction and processing, as well as 10 % of the initial capital equipment costs [161]. Recycling aluminium typically involves two main methods: melting or casting and solid-state recycling. Currently, the predominant approach in most industries involves the melting technique, where aluminium scrap is melted to produce a secondary ingot. The composition of the alloy is carefully controlled to meet standardized grades. The recycling process begins with the collection and sorting of aluminium scrap, followed by thorough cleaning. The scrap is then melted in furnaces, such as rotary or electric furnaces, to convert it into molten metal. The molten metal undergoes purification and adjustments to achieve the desired alloy composition. It is then shaped into a form suitable for subsequent processing or fabrication.

Through the use of solid-state recycling processes, several novel strategies for recycling aluminium chips have been developed. Firstly, powder metallurgy processes were employed for solid-state recycling, as determined by Gronostajski et al. [24] and later by Fogagnolo et al. [25]. However, more recently, advancements have been made in the solid-state technique with the development of a direct recycling approach, which eliminates the ball-milling step and produces fine granulated particles. This process is referred to as direct recycling. The direct recycling techniques involve processes such as hot extrusion, hot rolling, and others.

4.2. Discussion

Table 5 provides the condensed review of the nine research involving all sixteen scenarios. The range of publications is 2001–2022 (15 years) shown in Table 5 from 2001 to 2016. Additionally, the research was carried out from 2017 to 2022 using three different scenarios, as shown in Table 6, including landfill versus recycling (LvR), incineration versus recycling (IvR), and recycling (melting) versus recycling (solid-state). Hence, there are four studied out of nine studies make use of aluminium cans. Seven studies mapped on similar geographic region – Europe, whereas the rest are carried out in Australia, USA, Argentina, and China. Unitary is the most preferred functional unit and two studies, specifically Morris [162], and Manfredi et al. [163] used generation-based of waste collected in the household. In addition, four studies carried out the waste management based recycling aluminium by Refs. [164–167].

For system boundaries, one studies excluded primary production in the system, and only one study [168] utilized the complete system

Table 5
Summary of aluminium LCA's reviewed.

Publication Information		Year	2001	2001	2005		2011	2012	2012	2011	2015			2016
		Material	MSW	Al cans	Al cans		Al cans	Al Cans	Al chips	Al container	Al Chip			Al plate
		Geography	Europe	Australia	USA	Argentina	Spain	Europe	Europe	Europe	Belgium	Norway	Germany	Italy
		Author & Ref.	Smith et al. [168]	Grant et al. [170]	Morris et al. [162]		Pasqualino et al. [171]	Merrild et al. [172]	Paraskevas et al. [169]	Manfredi et al. [163]	Duflou et al. [173]			Ingarao et al. [174]
Scope	Functional Unit	Unitary	●	●			●	●	●		●	●	●	
		Generation-based			●	●				●				●
	System Boundaries	Primary production	●	●	●	●	●	●		●	●	●	●	●
		Capital goods	●											
		Collection/ Transportation	●	●	●	●	●	●		●				●
		Secondary products and final residuals	●				●	●	●	●	●	●	●	●
Life cycle inventory analysis	Data sources	Primary		●	●	●					●			●
		Database	●	●		●	●	●	●	●	●	●	●	●
		Literature							●					●
	Database		BUWAL	US EPA	N/A	DST	Ecoinvent	Easewaste	Ecoinvent	Easewaste	Ecoinvent			Ecoinvent
	Software		Ms. Excel	Simapro	DST	DST	N/A	Easewaste	Simapro	Easewaste	Simapro			N/A
Impact Assessment	Methods	CML		●										
		EDIP						●						
		TRACI			●	●								
		CED					●							
		ReCiPe							●		●	●	●	
		IPCC	●											
		Unspecified												●
	Impact Categories	Acidification (AC)			●	●		●		●				
		GWP	●	●	●	●	●	●		●				●
		POF						●		●				
		Nutrient enrichment						●		●				
		Environmental							●		●	●	●	
		Water use		●										
		Eutrophication			●	●								
	Damage categories	Human health			●	●			●		●	●	●	
		Resource depletion							●		●	●	●	
		Ecosystem quality			●	●			●		●	●	●	
		Unspecified	●				●	●		●				●
Interpretation	Sensitivity analysis		Emission assumption modeling	Landfill gas capture	N/A	N/A	Material amount	Impact potential	Substitution of material	Technology modeling	Scrap material possible			Material and end of life
	Uncertainty propagation		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Waste Handling Comparison (Scenario)			LvR	LvR	LvR IvR	LvR IvR	LvR IvR	IvR	$R_{M}vR_{S}$	LvR IvR	$R_{M}vR_{S}$ (SPS)	$R_{M}vR_{S}$ (Hot Extrusion)	$R_{M}vR_{S}$ (Screw Extrusion)	$R_{M}vR_{S}$
Conclusion	Landfill													
	Incineration													
	Recycling Melting	●	●	●	●	●	●		●					
	Recycling Solid-state							●		●	●	●	●	

GWP - Global warming potential; POF - Photochemical ozone formation.

Table 6
Life cycle assessment based waste handling comparison.

Country	Year	Landfill	Waste Handling Comparison	Incineration	Waste Handling Comparison	Recycling Melting	Recycling Solid-state	$R_M vR_S$ (SPS)	$R_M vR_S$	$R_M vR_S$ (Hot Extrusion)	$R_M vR_S$ (Screw Extrusion)	References
		L_{cans}	LvR_M	I	IvR_M	R_M	$R_{Solid-state}$	Waste Handling comparison				
United Kingdom	2017	●	●			●						[139]
Singapore	2017	●		●						●		[175]
Romania	2018	●	●									[176]
Italy	2018		●			●						[177]
USA	2019	●		●	●							[178]
Australia	2019	●		●					●			[179]
Italy	2020	●	●			●						[180]
Italy	2021	●				●			●			[181]
Germany	2021						●				●	[132]
Switzerland	2022			●	●							[182]
Germany	2022	●				●	●					[153]
China	2022						●		●			[183]

consists of initial primary production to final residuals of aluminium from MSW. On the other hand, studies by Paraskevas et al. [169] covered only the waste and by-product stream from production aluminium (secondary product). Most of the studies make use of the database as a data source and only three studies utilized site-specific data from field investigation. Strategies utilized as a part of effect evaluation were fluctuated from every one of the reviews and it relates to the chosen programming since a large portion of the generally utilized LCA programming incorporates a few operational LCIA techniques. Global warming potential (GWP) is clearly commanding analyst chose affect classes. Different classifications included are acidification (four reviews), Eutrophication (two reviews) and so forth. While, just two reviews recognized the harm classes includes. Sensitivity investigation was not quite the same as all reviews and lamentably, each of the nine reviews no plainly supported the vulnerability engendering technique in their papers.

One notable aspect of the discussion is depicted in Fig. 16, which presents a statistical analysis of the number of publications categorized into three distinct waste option comparisons. In recent literature, two prevalent waste management option comparisons are LvR (Landfill versus Recycling) and IvR (Incineration versus Recycling). Recycling emerges as the most favorable waste management option in both LvR and IvR scenarios. On the other hand, the RMvRS (Recycling versus Mechanical Sorting) scenario is represented by three studies, wherein a novel recycling technique known as solid-state recycling demonstrates a reduced environmental impact.

4.2.1. Landfill versus recycling (LvR)

In comparison to landfilling, recycling is clearly a more favorable

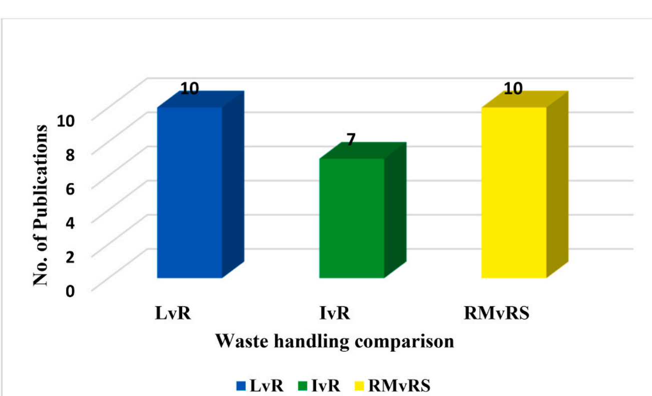

Fig. 16. Waste handling comparison (scenario).

option across all scenarios and environmental impact categories. Six scenarios that cover the whole life cycle and were created from numerous investigations form the basis of this finding. Smith et al. [168] determined that recycling provides a net greenhouse gas flux savings of 95 kg CO_2 equivalent per tonne of waste when compared to landfilling. Grant et al. [170], established that the recycling are able bring down ecological effect by roughly 47 % of the greenhouse savings are from evaded methane, which would have been created at landfill by the natural portions (it is accepted that 55 % of the methane created in the landfill is capture for electricity production) and the rest of the nursery reserve funds is because of the shirking of virgin material generation. The funds in water use over the framework are an aftereffect of lessened water utilization in virgin aluminium creation. According to Morris [162], recycling rates in both the USA and Argentina have been found to be 194 times more effective per ton of material handled compared to landfilling, even when considering energy generation from landfill gas, in terms of reducing global greenhouse gas emissions. Additionally, the environmental impact correlated with the assembly, handling, and transportation of recycled materials to the market is lower compared to the emissions resulting from using virgin materials to produce new items. Additionally, it was discovered that recycling reduced emissions five times more effectively than landfilling of acidifying substances, that contribute to environmental issues like acid rain, and thirteen times more effective in reducing emissions of atrophying substances that lead to ecological damage such as the nitrification of lakes and streams. Studies have shown that landfills contribute to increased potential adverse effects on human health and the ecosystem, including air pollution emissions and the release of toxic substances into water bodies. Pasqualino et al. [171] found that the impact of transportation increases with longer distances. According to the Global Warming Potential (GWP) indicator, an additional 100 km of transport is associated with an approximate increase of 0.035 kg CO_2 eq. The transportation of the packaged product significantly influences the overall life cycle impact of the product. According to Manfredi et al. [163], the landfilling of aluminium leads to a significant burden on toxicity-related categories, particularly eco-toxicity in water, with a value of 132 mPE/tonne. This is primarily caused by the release of aluminium, manganese, and copper from leachate emissions after treatment. Furthermore, recycling plays a crucial role in reducing and potentially eliminating the need for landfills. By diverting solid waste from landfills through recycling, the available landfill space can be utilized more efficiently. This is especially important as finding new landfill sites in urban areas becomes increasingly challenging. Recycling helps to extend the lifespan of existing landfills by decreasing the amount of waste that needs to be placed of, thereby making each landfill last longer.

4.2.2. Incineration versus recycling (IvR)

Incineration as opposed to reusing situations additionally inferred that reusing was the most positive choice contrasted and cremation depended on five situations from various reviews including the entire life cycle. Burning produces, a scope of unpredictable and gas emanations, which discharged to the air, can bargain natural quality. Morris [162], comprised that for both regions, the GWP, acidification and eutrophying substances exhibit lower impact of consuming recycling instead of incineration. Incineration prompts to increments in potential antagonistic effects on human wellbeing and biological framework connected with criteria air contamination emanation and with the arrival of dangerous elements to the climate. Pasqualino [171], because burning aluminium produces pollutants, uses energy, and leaves behind slag to the aluminium consume energy, generate emissions and slag residues when they are incinerated. Manfredi et al. concluded that incineration caused potential impacts to GWP, mainly in terms of Nutrient Enrichment and Acidification, as this percentage cannot be used to recover energy [163]. Regarding the toxicity-related categories, various management alternatives were evaluated, and notable impacts were observed, particularly in terms of eco-toxicity in water (chronic) and human-toxicity via water. Incineration, for instance, showed potential impacts of up to 29 mPE/tonne for eco-toxicity in water and 12 mPE/tonne for human-toxicity via water. On the other hand, according to Merrild et al. [172], the studies consistently indicate that recycling is preferable to incineration for metal waste. Compared to using virgin raw materials, recycling not only saves a substantial amount of energy and resources but also does not contribute to energy generation at the incineration plant. Metal recycling demonstrates benefits in categories such as fermentation and net energy consumption, although there was no significant difference between recycling and thermal treatment in the category of global warming potential.

Recycling offers the advantage of reducing both air and water pollution compared to incineration. Through the recycling process, there is a decrease in air pollution generated by power plants and a reduction in water pollution caused by chemicals used in manufacturing. Inefficient plant design and inadequate operating standards in incinerators have led to a lack of control over combustion conditions, resulting in the release of smoke, odors, and significant levels of residual organic matter in the ash. Incineration facilities have been identified as significant sources of heavy metals, dust, acid gases, and by products of incomplete combustion, including dioxins and other toxic organic micro-pollutants, posing a risk to urban environments.

4.2.3. Recycling (melting) versus recycling (solid-state) ($R_M vR_S$)

Three studies conducted by Paraskevas et al. [169], Duflou et al. [173], and Ingarao et al. [174] examined eight scenarios comparing recycling through melting and recycling through solid-state techniques. These scenarios involved various processes such as hot extrusion, screw extrusion, and spark plasma sintering (SPS). The studies concluded that recycling through solid-state techniques offers significant environmental advantages, primarily by avoiding metal losses during secondary aluminium production. According to Paraskevas et al. [169], in conventional recycling, the greatest impact on the total environmental impact arises from the loss of metal during the production of secondary ingots, which is then substituted by primary aluminium. This metal loss accounts for approximately 70 % of the 10 % aluminium lost during secondary production. Each 5 % loss of aluminium results in an impact of 72 mPt, which is 4.6 times the total impact of the entire alternative recycling process. Additionally, the inclusion of magnesium as an alloying element during recycling contributes to the overall environmental impact by 10 %. The remaining portion of the impact stems from the energy consumption (thermal and electricity) associated with the secondary re-melting and casting step.

The study conducted by Duflou et al. [173] concluded that recycling through solid-state techniques has a lower environmental impact compared to incineration of aluminium, as the combustion of aluminium consumes energy, generates emissions, and leads to slag formation. The research found that the recycling processes considered in their study demonstrated a reduction factor of 2–4 for waste material losses compared to typical industrial loss divisions. In the case of the spark plasma sintering (SPS) process, the reduction factor could reach up to 2.5, depending on the severity of oxidation losses and the presence of turnings with high material losses of 16 % or higher. This reduction factor is particularly significant for scrap types with a high surface-to-volume ratio, as the solid-state recycling approach avoids substantial material losses that occur through heavy oxidation in conventional remelting methods. Therefore, for small-volume waste, such as chips, solid-state recycling is considered a preferable waste management option.

Ingarao et al. [174] conducted a comparison between two different recycling technologies and observed that the solid-state recycling approach provides significant benefits. This is attributed to the dual advantages offered by solid-state recycling: reduced process energy consumption and emissions, as well as decreased material losses. Even when considering the best scenario for traditional remelting (CR-5%), the solid-state recycling method achieved remarkable reductions of 75 % in energy consumption and 62 % in CO_2 emissions.

In current industry practices, Aluminium is generally recycled via a melting process to create a secondary ingot. The composition of the alloy is meticulously regulated to match standardised standards. However, there are metal losses throughout this process that need to be made up for using primary aluminium. Inefficiently, primary aluminium production is known to be highly energy-intensive, with an average energy requirement of 66 MJ per kg in 2012. The Hall-Héroult process [184], which relies heavily on electricity, accounts for 80 % of this energy consumption. Additionally, the greenhouse gas emissions associated with the global aluminium cycle in 2007 amounted to approximately 0.45 gigatons of CO2 equivalent, representing roughly 1 % of global GHG emissions [185]. The primary processes involved in aluminium production, such as smelting, mining, refining, and anode production, contribute significantly to over 90 % of the total emissions. The energy utilized throughout the production chain has a substantial impact on emissions and environmental effects due to variations in power generation methods. Indirect emissions, primarily from electricity production, account for the largest portion of emissions (65 % of the total), followed by process emissions (18 %) and fossil fuel emissions (17 %) [184]. Furthermore, the recycling process through melting incurs losses at each stage. These losses occur when the metal oxidizes during melting, when some of the metal is assimilated into the slag, and during casting and further processing of aluminium ingots [20]. The melting process results in significant alloy losses due to oxidation, and the costs associated with more efficient recovery, in terms of labour and energy, are prohibitively high [19].

Through conventional recycling methods, aluminium alloy scraps are subjected to melting to recover and incorporate some of the alloy into the production process. The melting process requires heating to temperatures exceeding 1,000 K (Suzuki et al., 2007). However, significant losses of aluminium metal occur during this conventional process. These losses stem from deficits in metal content during remelting, the formation of by-products during liquid aluminium processing, the generation of scrap during casting, and the production of butts during extrusion, which contribute to the creation of new scrap [99]. It is estimated that approximately 10 % of aluminium metal is lost during remelting, and an additional 35 % is generated as new scrap throughout the process. In total, around 45 % of the aluminium metal is either lost or transformed into new scrap. Puga et al. [86] also emphasized the low metal recovery rate, high energy consumption, and the emission of significant amounts of smoke and gases into the environment associated with this process.

In contrast, the utilization of solid-state recycling techniques significantly reduces the energy requirements compared to the conventional process chain, particularly during the re-melting stage for producing new extrusion billets. This approach typically utilizes only 5–10 % of the energy consumed in the conventional process [26]. Samuel [20] described this technique as a streamlined process with improved recovery efficiency and reduced generation of new scrap. According to Gronostajski et al. [19], the solid-state recycling method allows for the recovery of approximately 95 % of the metal, utilizing just a gigajoule of energy per ton, and requiring only 2.5–6.5 man-hours per ton. The implementation of this alternative recycling technique has the potential to decrease expenditures on environmental protection, lower the consumption of ores, reduce reliance on energy sources, and mitigate environmental degradation by minimizing air pollution emissions [1,66].

5. Conclusions and future trends

This systematic review provides appropriate alternatives for helping decision-makers use multi-criteria decision analysis for recycling aluminium techniques. In this intensive review, three recycling techniques, i.e., conventional recycling (CR), semi-direct recycling (SDR) and direct recycling (DR), were reviewed. Current aluminium recycling practices via melting techniques, in which the temperature exceeds the melting point, are CR methods. The SDR technique includes a preprocessing step before performing the main process of powder metallurgy and/or hot extrusion. DR only requires a single step to produce the final products. Currently, there are only two processes that have been recognized as DR techniques: cold and hot forging.

Publications on aluminium recycling originally introduced the melting technique in the early 1980s. The process evolved in 1996 with the invention of the solid-state recycling technique. Moreover, newly developed approaches were introduced in 2012. Parallel to this evolution, researchers have aimed to reduce the number of steps, which can diminish energy needs and reduce production costs. Waste reductions have led to relatively eco-friendly solutions, indicating increasing awareness of sustainable manufacturing among researchers. In the future, DR techniques still have much knowledge and contribution gaps that must be explored. We recommend that additional studies on DR techniques are needed to ensure knowledge continuity and environmental sustainability.

In terms of Life Cycle Assessments (LCAs), The findings, which are consistent, show that recycling, when compared to other waste management strategies, often delivers higher environmental advantages and lower environmental consequences. Recycling contributes to greenhouse gas reductions by avoiding methane emissions, and it also saves water and further reduces greenhouse gas emissions by minimizing the production of virgin materials. The environmental benefits highlighted in this study emphasize the importance of integrating recycling into sustainable waste management and resource efficiency practices, which contribute significantly to lowering greenhouse gas emissions. Additionally, it is recommended to conduct LCA studies specifically on recycling (solid-state) to further enhance our understanding and realize substantial environmental benefits. The future trends would be more focused on the application of processed recycled materials towards green manufacturing technology, this initiative proposes simple, low-cost, direct recycling methods without interfering with metallurgical operations. In comparison to the traditional approach, it potentially offers reduced air pollution and excellent raw metal usage. As a result, this effort will help businesses involved in solid waste management and green technology as a means of preventing global warming, lowering the amount of solid waste produced for landfills, and conserving energy. The goal of this effort, which is known as sustainable manufacturing, is to produce goods using methods that have a minimal negative impact on the environment, conserve energy and natural resources, are safe for communities, and are economically advantageous for the construction, transportation, and automotive industries. One potential future challenge is the development of more advanced and efficient aluminium waste classification technologies. Improved sorting methods can increase the quality and recovery rate of recycled aluminium, resulting in a more sustainable recycling process. As the world continues to shift towards renewable energies, the aluminium recycling industry may also shift towards cleaner and more sustainable energy. Renewable energy in recycling plants has the potential to significantly reduce the carbon footprint associated with aluminium recycling. Smart recycling technologies, such as AI-driven sorting systems and data analysis, can improve the efficiency and precision of aluminium recycling processes, improve resource utilization, and reduce waste.

CRediT authorship contribution statement

Sami Al-Alimi: Conceptualization, Methodology, Software, Validation, Writing – original draft. **Nur Kamilah Yusuf:** Conceptualization, Resources, Supervision. **Atef M. Ghaleb:** Data curation, Funding acquisition, Validation, Visualization, Writing – review & editing. **Mohd Amri Lajis:** Investigation, Project administration, Resources. **Shazarel Shamsudin:** Investigation, Project administration. **Wenbin Zhou:** Investigation, Writing – review & editing. **Yahya M. Altharan:** Data curation. **Hamza Salah Abdulwahab:** Formal analysis, Software. **Yazid Saif:** Software, Validation. **Djamal Hissein Didane:** Validation, Visualization, Writing – review & editing. **Ikhwan S T T:** Formal analysis, Resources. **Anbia Adam:** Funding acquisition, Writing – review & editing.

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.

Data availability

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

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