Recycling and Reuse of Basalt Fiber Reinforced Resin Materials with Artificial Intelligence Technology

Abstract: Landfill and incineration of obsoleted Basalt Fiber Reinforced Resin (BFRR) not only waste resources, but also pollute environment. Therefore, this study investigates the stock, environmental hazards, and recycling value of waste BFRR, analyze the current BFRR recycling technologies, and summarizes the current challenges and future development of BFRR recycling. The results show that the amount of obsoleted BFRR is increasing, but traditional disposal methods are challenging for efficient resource utilization while also causing environmental pollution. Emerging disposal methods also have certain drawbacks, such as the most severe damage to recycled Basalt Fiber (BF) reaching 80%, low recycling rates, and some methods needing help to recover resin. Regenerated BF can be used for material reinforcement, 3D printing material preparation, and component production, while resin recycling materials can be used in the chemical industry. Digital image processing technology and artificial intelligence (AI) are effectively utilized to monitor the durability of BFRR material and identify its recycling trace. Integration of AI-generated big data enhances the efficiency of BFRR material recycling, contributing to environmental protection. Overall, the investigation and advancement of BFRR recycling are still in their nascent stages. Moving forward, it is imperative to delve deeper into exploring more efficient and intelligent environmentally sustainable recycling methodologies aimed at minimizing recycling expenses. This endeavor will facilitate the repurposing of waste materials, consequently mitigating the environmental footprint of waste.

Keywords: BFRR, Environmental Protection, AI Recycling, Development Prospects.

I. INTRODUCTION

BF is a type of fiber produced by subjecting basalt to high-temperature melting and spinning processes. It has excellent physical and mechanical properties such as thermal, acoustic, tensile and compressive strength, high electrical insulation, and corrosion resistance. Compared with various fibers in traditional composite materials, as shown in Table 1, BF has a wider temperature range and better heat resistance than glass fiber. Although the tensile strength of BF is similar to that of carbon fiber, the cost of BF is lower. In addition, BF also has advantages such as low energy consumption, simple process, and high utilization of raw materials[1]. BFRR is widely used in building, petroleum transportation, and precision manufacturing due to its environmentally friendly, green properties, high strength, corrosion resistance, and cost-effectiveness [2-3].
Table 1. Comparison of BF with various fibers in terms of main parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>BF</th>
<th>Glass fiber</th>
<th>Carbon fiber</th>
</tr>
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<tbody>
<tr>
<td>Young's modulus (GPa)</td>
<td>89</td>
<td>85</td>
<td>241</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>3.15</td>
<td>5.3</td>
<td>1.5~2.0</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.65</td>
<td>2.49</td>
<td>1.8</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>3000~3500</td>
<td>4590~4830</td>
<td>2500~3500</td>
</tr>
<tr>
<td>Softening point/°C (η=107.6dPaS)</td>
<td>1056</td>
<td>960</td>
<td></td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>-260~700</td>
<td>-50~380</td>
<td>50~700</td>
</tr>
<tr>
<td>Cost USD/kg</td>
<td>2.6~3</td>
<td>2.6~3</td>
<td>25~50</td>
</tr>
</tbody>
</table>

However, with the continuous expansion of the application scope of BFRR, the amount of discarded BFRR is gradually increasing, becoming an important source of environmental pollution. As a new eco-friendly material, how to efficiently recycle BFRR waste and achieve sustainable development has become an urgent environmental and resource issue [4]. Although the traditional landfill and incineration methods for treating BFRR waste have relatively simple processes, they cause significant environmental pollution and cannot effectively utilize the raw materials. The EU has issued multiple regulations requiring member states to prioritize resource recovery in solid waste treatment and avoid using terminal treatment methods such as landfill and incineration.

Therefore, exploring new methods for recycling BFRP has become a crucial way to solve the problem of BFRP waste pollution. Currently, the research on BFRR recycling technology [5] mainly refers to the recycling technology of carbon fiber and glass fiber. The recovery process mainly uses mechanical, pyrolysis, and chemical methods [6]. After separation, BF and resin can play a role in many aspects after simple processes such as cleaning and purification. For example, waste BF can be used as concrete filling material, high-strength environmental protection wallboard, composite asphalt filling for road construction; resin can be decomposed into small molecule substances for the production of organic fertilizer; mechanically separated BFRR can be re-molded to prepare profiles, etc.

However, the effective recycling of BFRR faces significant challenges due to the limited degree of informatization and intelligence in current recycling technologies, as well as the complexity of BFRR structure and the diverse sources of BFRR waste [5]. For example, mechanical recycling methods are simple but cause significant damage to the BF, chemical separation has a high recovery rate. However, it is detrimental to the environment, pyrolysis recycling can achieve mass production but consumes a large amount of energy [7, 8]. In addition, there are relatively few studies and application cases related to the recycling of BFRR waste, and the lack of data hinders the further development of BFRR waste recycling.

Therefore, this article first explores the significance of recycling BFRR waste, analyzes the advantages and disadvantages of different recycling technologies, and lays the foundation for researching new BFRR recycling technologies. Secondly, the current status of BFRR waste recycling and the application direction of recycled products are studied, a new BFRR recycling process is proposed, and the development trend of BFRR recycling in the AI era is predicted. Finally, regarding the current development difficulties of BFRR recycling, this article presents prospects and suggestions for BFRR recycling research, aiming to provide theoretical basis and practical guidance for the recycling of BFRR.

II. THE SIGNIFICANCE OF BFRR RECYCLING

A. Current Application Status of BFRR.

Due to the benefit of BFRR's excellent physical and mechanical properties and acid and alkali resistance, the market size of BFRR continues to expand.

According to the statistics of Hunan Beizhesi Information Consulting Co., Ltd. and Zion Research in the United States, the compound annual growth rate of BF reached 10.7% during 2016-2021. The global BF market size reached 1.339 billion yuan in 2021. Among the various application fields of BFRR [7], construction is the largest application sub-market for BF. As early as 2018, PR Newswire made a statistical discovery that in 2012, the demand for construction accounted for 37% of the total demand, followed by transportation. The output value of the transportation market alone is expected to reach 18.3 million dollars in 2019. [9] This article lists the common applications of BFRR in various fields as shown in Figure 1.
In construction engineering, BFRR is mainly used as reinforcement in the form of rebar, geogrid, and anchor rod, replacing traditional rebar for strengthening concrete, anchoring slopes, and engineering support. In addition, BFRR can also be made into panels to divide interior areas and isolate noise, and used to manufacture building insulation materials, which enhances the thermal insulation of the building and also takes care of waterproofing. Automobile manufacturing is also a major application area for BFRR, commonly used for manufacturing vehicle body structures, interior decorations, seats, and other components. Its excellent impact resistance can protect the vehicle in a collision. Moreover, BFRR is also used in the brake systems of automobiles. In the petrochemical industry, BFRR can manufacture pipelines, high-pressure pipelines, and petrochemical storage tanks. Compared with traditional steel pipelines, BFRR pipelines are lighter, more durable, and environmentally friendly, reducing manufacturing and maintenance costs and improving pipeline service life. BFRR also has wide applications in the aerospace field, not only used for manufacturing the shell of aircraft and satellites, such as fuselage, wings, tail wings, and wheel covers, but also for manufacturing thermal protection covers of spacecraft. In addition, BFRR has relevant applications in sports facilities, energy conservation, and environmental protection. With the prompt development of technology and the continuous improvement of material requirements, excellent properties of BFRR such as lightweight, high strength, high-temperature resistance, corrosion resistance, and durability will make it an indispensable material in many fields.

B. Environmental Challenges of BFRR

In the future, the usage of BFRR will continue to increase. By 2027, the global BF market size will increase from $286 million to $517 million, with a compound annual growth rate of approximately 12.5% from 2022 to 2027. However, as the widespread use of BFRR continues, the amount of BFRR waste is also increasing. The main sources of BFRR waste include scraps generated during cutting, splicing, and repair processes in production. At the same time, unqualified products are produced during building construction due to production efficiency and process limitations. In addition, aging, damaged, deformed building components, pipes, scrapped parts from aircraft and cars, are major sources of BFRR waste.

The disposal of BFRR waste well cause serious environmental pollution and waste of resources. For example, organic matter decomposes into harmful gases and microscopic particles, waste accumulation leads to waste of land resources, as the waste cannot be fully utilized. However, although the traditional landfill method is easy to implement, has low costs, the treatment process will produce leachate, which cause environmental pollution. Studies have also found that BF in BFRR is not easily decomposed, with a complete degradation time of about 50-100 years. Although incineration can reduce the storage space of waste and does not produce leachate, it produces ash and exhaust gases when dealing with BFRR waste. Moreover, the incineration process cannot completely burn the inorganic components in composite materials.

However, the current BFRR recycling technology is still in the preliminary stage. Figure 2 shows the data on the number of BFRR-related research papers. This study found 20,500 studies on BFRR from 1985 to 2022 through a search of BFRR-related technology research in Google Scholar. The annual growth trend of BFRR-
related studies is shown in Figure 2(a), which shows an overall upward trend. However, research on BFRR recycling technology only accounts for 18.24% of the total research quantity, as shown in Figure 2(b), which is only 3.79% of carbon fiber and 38.32% of glass and 56.94% of aramid fiber. After analyzing the titles, purposes, and new findings of the research papers, the author found that only 27 studies accurately described BFRR recycling technology. Therefore, there is an urgent need to find a green and efficient circular utilization technology for BFRR.

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C. The Circular Utilization Benefits of BFRR

The BFRR circular utilization has high economic, environmental, and social benefits. From an economic perspective, recycling BFRR waste can help reduce production costs and improve a company's core competitiveness and market share. With increasingly strict environmental regulations, recycling BFRR waste can also help companies reduce waste disposal and environmental protection costs, and enhance their social image and brand value\[14\].
Waste recycling lays a solid foundation for environmental protection and sustainable development [14]. This action can not only maximize resource utilization, reduce resource consumption and waste, and reduce the generation of solid waste [15], but also reduce energy consumption in the processing, avoid adverse environmental impacts of waste accumulation and discharge. It can also reduce the demand for new raw materials, ease the tight supply of raw materials, reduce energy consumption in production, and contribute to environmental sustainability [16].

From a social perspective, waste recycling can raise public awareness and concern for environmental issues, improve the public's environmental awareness, sense of responsibility, gradually create an atmosphere and culture of nationwide environmental protection from an individual perspective [16]. The recycling of waste requires the investment of various technologies, equipment, talents, and resources. Waste recycling can provide new industry chains and business opportunities and promote the development and application of environmental protection industry technology.

III. THE CURRENT STATUS OF BFRR RECYCLING TECHNOLOGY

A. Types of Recycling Technologies

Several common recycling methods for fiber-reinforced resin (FRR) waste are mechanical, pyrolysis, and chemical recycling [17]. Figure 3(a) shows that the mechanical recycling method only requires cutting, crushing, and screening processes to effectively separate fibers from resin. The pyrolysis method can be divided into high-temperature, fluidized bed pyrolysis, and microwave pyrolysis depending on the processing environment [18, 19]. The specific process of pyrolysis is shown in Figures 3(b), (c), and (d). In all three methods, resin is decomposed under high temperature and special atmosphere, the decomposition products are evaporated by heat and pressure to separate resin and fibers. However, high-temperature pyrolysis only achieves the purpose of high-temperature decomposition, fluidized bed pyrolysis separates fibers and resin by controlling the temperature distribution and material fluidization. In contrast, microwave pyrolysis uses high-frequency electromagnetic waves to generate a thermal effect in the waste, achieving the purpose of resin decomposition. Chemical dissociation is a method of placing waste in a solvent and using chemical reactions to dissociate polymer molecules in the waste. The valuable components are then recovered using related technologies [18]. The process flow of treating BFRR waste by chemical recycling is shown in Figure 3(e).

Englund [20] et al. used a hammer mill to crush aerospace industry waste. They mechanically tested the re-compact material, finding that the mechanical properties decreased by at least 50-60% compared to the original composite material. Due to the severe damage to the fiber's mechanical properties caused by mechanical recycling, mechanical recycling is mainly used for waste pretreatment to improve the reaction and recovery rates in subsequent processes. Meyer, L.O. et al. found that small-scale carbon fiber recovery using high-temperature pyrolysis could maintain 80% of the original stiffness of the fibers, with lower mechanical performance loss compared to mechanical recycling. Compared to high-temperature pyrolysis, fluidized bed pyrolysis can achieve continuous feeding and discharging [21], and use the heat of resin decomposition in the pyrolysis process to reduce energy consumption. Fluidized bed pyrolysis has been used for large-scale industrial carbon fiber recovery [21]. However, due to the friction and shear pretreatment of the solid during the fluidization process, the recovered fibers are loose and disorderly, with mechanical performance losses exceeding 25% [22]. Therefore, some scholars have studied microwave methods that are more efficient and less damaging to fibers. They found that the strength of the fibers recovered by microwave pyrolysis decreased by less than 20%, and the fiber surface was cleaner and smoother. Lester et al. found that 3KW multi-mode microwave resonator could achieve complete recovery of CF in 8 seconds [23]. However, due to the development of microwave equipment and other reasons, microwave methods for processing FRR have not yet been widely scaled, and only a few companies have established continuous microwave recycling devices for carbon fiber composite materials, such as the Firebird Advanced Materials Company in North Carolina, USA [24]. Jiang et al. [25] first treated the fiber with acid and then treated it in polyethylene glycol at 160°C for 200 minutes. The obtained fiber's tensile strength remained at 95% of the original fiber, and the resin removal rate was as high as 95wt%.
Figure 3. The Process Flowchart of BFRR Waste Recycling Includes.
In order to find a batch green and efficient FRR waste recycling scheme, this article compares the above three methods from the aspects of processing temperature, energy consumption, global warming potential, fiber performance retention, etc., as shown in Table 2.

<table>
<thead>
<tr>
<th>Method</th>
<th>recycled BF’s performance (%)</th>
<th>Batch production</th>
<th>Processing temperature (°C)</th>
<th>Energy consumption MJ/kg</th>
<th>Global warming potential CO2eq/kg BFRR</th>
<th>Resin separation rate(%)</th>
<th>advantages</th>
<th>disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>40%~50%</td>
<td>√</td>
<td>room temperature</td>
<td>1.12~1.2</td>
<td>0.11~1.8</td>
<td>70</td>
<td>Simple process, low cost, no pollution</td>
<td>Low recovery rate, Severe BF damage</td>
</tr>
<tr>
<td>Chemical</td>
<td>80%~90.5%</td>
<td>√</td>
<td>250~400</td>
<td>38.39</td>
<td>1.53</td>
<td>99.18</td>
<td>Resin can be recovered, high recovery rate</td>
<td>Environmental impact, long processing time</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-temperature pyrolysis</td>
<td>20%~50%</td>
<td>√</td>
<td>350~800</td>
<td>37.36</td>
<td>2.9</td>
<td>67</td>
<td>Wide applicability, high capacity</td>
<td>High energy consumption, waste gas generation</td>
</tr>
<tr>
<td>Fluidized bed pyrolysis</td>
<td>50%</td>
<td>√</td>
<td>400~600</td>
<td>10.25</td>
<td>1.56</td>
<td>70</td>
<td>Clean BF surface, high controllability, high recovery rate</td>
<td>Severe damage to fibers, high energy consumption</td>
</tr>
<tr>
<td>Microwave pyrolysis</td>
<td>75%</td>
<td>√</td>
<td>300~600</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>Clean surface, fast reaction rate</td>
<td>High cost</td>
</tr>
</tbody>
</table>

Through the table, it can be found that all three methods can achieve the bulk recovery of fibers. Among them, the mechanical recovery method has simple process, low cost, and does not produce pollutants, but its recovery rate is relatively low and the fiber performance is severely damaged. High-temperature pyrolysis and fluidized bed method can recover heavily polluted waste, but the fiber damage can be as high as 80% and cannot recover resin. Microwave pyrolysis can harvest clean BF with less damage to performance and achieve the recovery and utilization of resin quickly, but the equipment cost is relatively high. The chemical decomposition method has low energy consumption, high recovery rate, fiber damage not exceeding 20%, and high value of recovered products. However, using chemical reagents may cause some environmental problems and increase costs.

B. BFRR Recovery Technology

The above methods are more applied to the recycling of waste glass fiber and carbon fiber composite resin materials. To obtain a more excellent low-energy and high-efficiency BFRR recycling method, scholars have studied the BFRR waste recycling process by referring to the above two fiber composite resin waste recycling methods.

Volkov et al. [26] conducted thermal treatment on waste BFRR at 250°C and cut the softened steel bars into 4x450mm fragments before adding them back into the concrete. They found that the concrete with 0.1% of waste BFRR had a 50% higher bearing capacity than the original strength under 10 times the limit elongation of the concrete. However, Chen et al. [27] found that cutting fibers in mechanical recycling would seriously reduce the mechanical properties of BF. The tensile strength and flexural strength of BF decreased by 65% and 85%. The tensile and flexural moduli decreased by 50%. Furthermore, some scholars have found that BFRR has excellent high-temperature stability. Compared with ordinary resin, the thermal stability of BFRR has increased by 100°C, and the thermal degradation strength has decreased by 30%~60% [28]. However, when Bhat used thermal recycling(450~600°C) to recycle BFRR, he found that the BF strength loss exceeded 65% after two hours of treatment at the commonly used waste thermal recycling temperature [12]. Balaji et al. [29] believed that the pyrolysis of thermosetting materials would produce polluting gases, and using pyrolysis for recycling had certain environmental challenges. In order to solve the problem of serious loss of fiber mechanical properties in the pyrolysis recycling method, Lilli [5] treated the thermally recycled BF with 3mol NaOH at 400°C for 25 minutes and found that the recovery rate of BF strength reached 94%. Moreover, NaOH could also remove the carbon residue on the surface of BF well. In addition, Livia Persico et al. [30] utilized a solution of ice acetic acid and hydrogen peroxide at 160°C to chemically degrade BFRR. They successfully obtained a resin-free BF that was dense and clean. Their experiments demonstrated that the recovered BF exhibited a fracture toughness as high as
90.5% of the original fiber. An added benefit of this method is that the solvent can be recycled through distillation during processing, and the resin decomposition products can be separated for further reuse.

C. Exploration of BFRR Recycling Technology

By summarizing the above methods, combining them with the actual BFRR recycling status and its various properties in daily life, this paper explores the industrialized recycling process of BFRR waste. The BFRR recycling process is shown in Figure 4. Considering that fluidized bed pyrolysis is currently one of the most extensive used methods in industry for recycling fiber-reinforced composite resins, which can batch-process heavily polluted components and recover BFRR with high efficiency and low damage using chemical decomposition [20, 30]. This process mainly uses the above two methods to recycle BFRR. First, by discriminating the degree of pollution of the recycled materials, BFRR with severe pollution and obvious aging is recycled through fluidized bed pyrolysis, while BFRR with less pollution and higher recycling value is recycled through chemical decomposition. Before recycling, large components are cut and crushed to improve subsequent reaction efficiency.

In addition, this process improves the low rate of conventional chemical decomposition of BFRR. Before acid treatment, BFRR is subjected to swelling and preheating treatment in a solution above the resin glass transition temperature to increase the gap between BF and resin to accelerate the acid corrosion rate. In addition, this paper refers to the use of ultrasound oscillation technology by Meyer et al. [4] to assist in the recycling of BFRR, reducing the use of chemical reagents and making the recycling process more efficient, energy-saving and environmentally friendly.

IV. BFRR RECYCLING TECHNOLOGY IN THE AI ERA

BFRR waste originates from diverse sources, exhibiting varying material states and structural properties, thereby rendering its recycling technology exceptionally complex. Relying solely on a single, non-targeted recycling technique fails to ensure the stability of recycled products. Instead, it may result in significant material damage, low utilization rates, wasteful resource expenditure, and environmental pollution. To enhance the efficiency and effectiveness of BFRR recycling across multiple dimensions, including monitoring the degradation resistance of recycled products and conducting real-time environmental surveillance during the recycling process, comprehensive research and in-depth analysis of factors such as material origins, recycling methodologies, and operational environments are imperative. Nonetheless, undertaking such research tasks is formidable and intricate. Traditional mechanical testing methods, characterized by their time-consuming nature, labor intensiveness, exorbitant costs, and susceptibility to errors stemming from equipment malfunctions, often fall short in meeting the required standards. Fortunately, in the era of artificial intelligence (AI), these challenges can be mitigated through the establishment of extensive databases and the implementation of AI-driven simulation monitoring systems. Illustrated in Figure 5, the BFRR recycling data intelligence system comprises two components. Firstly, the BFRR large database stores a wealth of information pertaining to materials, recycling
techniques, and environmental impacts during the recycling process. Secondly, technological optimization, performance prognostication, and intelligent monitoring are achieved through AI model training and evaluation.

Figure 5. BFRR Recycling Data Intelligence System

The establishment of a database lays the groundwork for achieving multi-dimensional information intelligence in BFRR recycling. As early as 2012, Mehrez et al.\textsuperscript{[31, 32]} constructed an elastic modulus experimental database comprising twenty-one specimens and later devised a probabilistic method to integrate the experimental data into a stochastic model of the elastic modulus for heterogeneous composite structures. The creation of a BFRR recycling database not only streamlines the collection, organization, and storage of extensive data but also facilitates the circulation and exchange of information, thereby enhancing the reliability and consistency of the data\textsuperscript{[33]}.

Integrating advanced intelligent algorithms with machine learning models to delve into data information deeply proves to be an effective strategy for achieving high-performance green recycling of BFRR\textsuperscript{[34]}. Zhou\textsuperscript{[35]} illustrated a general workflow for material discovery and design based on machine learning models, as depicted in Figure 6. Following the establishment and validation of the model, optimal materials are identified and synthesized, with their actual performance verified through experimentation. In the BFRR recycling process, a similar approach can be adopted by simulating the variation of BFRR material properties under various recycling technologies and application scenarios. This facilitates the estimation of energy consumption during production, the design of production conditions, and the assessment of changes in material performance. Subsequently, intelligent algorithms can be employed to optimize recycling process parameters, thereby enhancing production efficiency, reducing energy consumption, and minimizing carbon emissions.
A. Existing Challenge

The recycling technology of BFRR is still in the early stage, and only a few studies have been conducted on the recycling of BFRR waste. Although some research has studied the feasibility of BFRR waste recycling by referring to other FRR waste recycling methods, these methods still have certain limitations and difficulties, such as high energy consumption in pyrolysis method, environmental pollution in chemical decomposition method, and significant fiber damage in mechanical recycling method.

The regenerability of BFRR is also a challenge. Although some companies have processed and manufactured regenerated products from BFRR, due to the special properties of the material composition, the recycled material is difficult to have the same performance and service life as the original material. In addition, the current demand for BFRR recycling in the composite material market is smaller than that in the native BFRR production market. There are relatively few cases of BFRR recycling, and specific data on the service life and performance of recycled BF are limited, which has caused certain difficulties in material blending design. Currently, there is a lack of standards and specifications for BFRR recycling, resulting in significant differences in the recycling methods and effects adopted by different research units, making it difficult to form a unified recycling system.

While AI technology has made significant strides across various domains, its integration into BFRR recycling encounters several challenges. Establishing intelligent systems necessitates extensive datasets for training and optimization. However, research on BFRR recycling remains relatively limited, leading to an inadequate accumulation of datasets. Additionally, the complexity and diversity of BFRR materials demand intelligent systems with a high level of adaptability to navigate various potential scenarios.

B. Outlook and Suggestions

With the widespread application of BFRR, waste recycling has become an urgent problem to be solved. In order to achieve sustainable development and utilization of waste, BFRR recycling technology needs to be continuously improved and innovated. To accelerate the development of BFRR waste recycling, this article proposes suggestions in the following two aspects:

• (1) Improve recycling technology. Strengthen basic research on BFRR, develop new separation equipment and technologies based on the specific physical and chemical characteristics of BFRR. For example, study cutting-edge technologies such as ultrasound, microwave, and optical techniques, and apply new catalysts, efficient filtering materials, etc. to BFRR separation processes. Reduce the damage caused to BF during the recovery process, improve the recovery rate of resin, and achieve more efficient, energy-saving, and low-cost purposes. Strengthen research on damaged fiber repair, and other multiple aspects.

• (2) Establish relevant standards. Fully consider the properties, sources, and types of waste, formulate reasonable recycling and treatment processes, establish corresponding quality inspection standards, ensure the quality and safety of recycled products, improve industry competitiveness, and promote the sustainable development of basalt fiber reinforced polymer composites.

• (3) Enhancing the informatization and intelligence of BFRR recycling applications involves establishing a comprehensive BFRR recycling database and leveraging AI-powered simulation monitoring technologies. This enables intelligent management and optimization of the entire BFRR recycling process, leading
to significantly improved efficiency and accuracy. It also offers more reliable technical support for the sustainable utilization of BFRR waste.

VI. CONCLUSIONS

This article explores the significance of researching BFRR recycling, its technical advancements, and reuse scenarios, while also outlining the current status and challenges within BFRR recycling technology. Key conclusions drawn include:

Given the increasingly stringent waste regulations worldwide and the expanding use of BFRR, the urgency of researching BFRR waste recycling technology is evident. This research not only aligns with sustainable green development goals but also aids in environmental protection and resource conservation. Despite various types of FRR recovery technology research, conventional methods still face issues such as environmental pollution, fiber damage, and low recovery rates.

Establishing a comprehensive database and integrating AI monitoring and evaluation are crucial steps toward developing high-performance regenerated products from BFRR and achieving sustainable industrial development. While current BFRR recycling technologies are still nascent, continuous technological advancements are expected to lead to more mature and intelligent approaches in the future. The creation of a comprehensive BFRR recycling database will offer more reliable technical support for future material manufacturing and applications. Therefore, this article suggests strengthening research on BFRR waste recycling and reuse technologies, integrating new technologies into the BFRR waste recycling and reuse process, and promoting the advancement of BFRR recycling and reuse through information intelligence.

ACKNOWLEDGMENTS

This study was financially supported by the Key R & D Projects of Deyang City (Grant NO.2022SZ059, and Grant NO.2022SZ049), the Innovation Guidance Projects of Science and Technology Plan of Deyang City (Grant NO.2022SCZ088), and the Scientific Research Project of Sichuan College of Architectural Technology (Grant NO.2018JKJ11, and NO.2022KJ10), the Headquarters technology project of China Huaneng Group Co., LTD (Grant No. HNKJ21-H74), and Water and Wind Energy Storage Technology Innovation Center of Tibet Autonomous Region (No. XXZ20201ZD003G). The authors gratefully acknowledge these grants.

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