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White Paper

HPN002- Sustainable waste management scoping study

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Summary

The utilisation of fibre-reinforced polymer (FRP) composites in lightweight structures is rapidly increasing due to their exceptional strength-to-weight ratio, driving substantial growth across the aerospace, defence, construction, automotive, and renewable energy sectors. This report aims to synthesise key findings and insights on the current state of FRP composite recycling.

The project begins with a systematic literature review to examine global research and technological advancements in FRP recycling, laying a foundation for understanding best practices. Subsequently, data on FRP composite usage and recycling rates will be gathered through industry collaboration, publicly available sources, and global case studies. Statistical analysis will be employed to assess the current Australian context relative to international benchmarks, with particular attention to the properties and adoption potential of recycled fibres.

A survey has been developed to collect comprehensive data from FRP and related raw material producers, end users and recyclers. It captures information on products, production techniques, material consumption, end-user applications of FRP, recycling techniques, material efficiency, energy consumption, and waste management practices during production, at the end of service life, and throughout the recycling process. The survey also addresses the dynamics of the recycling market. The findings will provide insights into waste generation volumes, market trends, industry demand and concern, and environmental impacts, while assessing the feasibility of integrating recycled fibres into industrial processes. These insights are incorporated into the report to present a detailed overview of the current state of the Australian FRP industry.

Additionally, the project evaluates existing FRP recycling pathways in Australia in terms of efficiency, cost-effectiveness, and environmental impact through case study, technology readiness level, cost-benefit and life cycle analyses. Insights from stakeholders are integrated to explore the potential for automation as a means of enhancing cost-effectiveness and sustainability.

In general, this report provides an in-depth analysis of global best practices, waste production, usage and recycling rates, end-of-life technologies, waste management strategies, and actionable recommendations. This report is intended to serve as a valuable resource for industry stakeholders, government bodies, and academia, supporting the transition towards a circular economy in Australia.

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Glossary:

FRP: Fibre Reinforced Polymer
CFRP: Carbon Fibre Reinforced Polymer
GFRP: Glass Fibre Reinforced Polymer
CF: Carbon Fibre
GF: Glass Fibre
rCF: recycled Carbon Fibre
rGF: recycled Glass Fibre
rFRP: remanufactured Fibre Reinforced Polymer
ACM: Australian Composites Manufacturing
CRC: Cooperative Research Centres
TRL: Technology Readiness Level
CBA: Cost Benefit Analysis
LCA: Life cycle Analysis

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Section 1: Introduction

The Transformative Impact of Fibre-Reinforced Polymers (FRP) on Modern Society: Advancements, Applications, and Future Prospects

Fibre-reinforced polymers (FRPs) have emerged as transformative materials across numerous sectors, owing to their unique combination of high strength, low weight, corrosion resistance, and design versatility [1,2]. These properties make FRPs indispensable in modern applications, enabling advanced structural performance and extended service life compared to traditional materials. The impact of FRPs is evident across multiple industries, including construction, transportation, aerospace, sports, and renewable energy, where they help meet growing demands for sustainability and efficiency [3].

ACM CRC Industry Partner Base

Advanced Engineering Partners:

FRPs are widely used in advanced engineering applications due to their superior mechanical properties and adaptability. Industries focused on cutting-edge structural solutions integrate FRPs to enhance product performance, efficiency, and sustainability. In the advanced construction industry, fibre-reinforced polymer composites are highly attractive for civil engineering applications due to their exceptional strength-to-weight and stiffness-to-weight ratios, corrosion resistance, light weight, and potential for high durability [1,4,5]. FRP is widely used for reinforcement in concrete structures, particularly in bridges, buildings, and utility infrastructure [6].

The use of glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) panels, or FRP-reinforced concrete, in new construction offers benefits such as free-form, tailorable design characteristics, strength-to-weight ratios far exceeding those of traditional civil engineering materials, and a high degree of chemical inertness in most environments—particularly in marine and coastal infrastructure [7-11]. Over 80% of highway construction agencies in the United States have used FRP materials in structural sections such as decks and culvert liners, with adoption dating back to the early 1990s [12]. FRPs have also seen extensive use in the construction industry in Australia. 96% of underground fuel tanks across Australasia are constructed from fibreglass with innovative resin systems developed within Australia [13].

As urban populations expand and infrastructure demands grow, ability of FRP to extend structural life aligns with sustainable development goals, especially by reducing the frequency and cost of repairs and replacements. Additionally, FRP can be applied in repair and retrofitting efforts, instantly reinforcing damaged structures and enhancing buildings' resistance to seismic and other forms of damage. The application of fibre reinforced polymer composites has grown significantly over the past decade, with annual waste generation increasing by approximately 20% over the last five years [14]. The building and construction sector became the largest end-use segment in the FRP market in recent years, accounting for over 40% of the global revenue share [15].

Consumer and Leisure Partners:

The consumer and leisure industry has undergone transformative advancements through the integration of fibre-reinforced polymers, particularly in the development of sports equipment and infrastructure. The incorporation of carbon fibre into sports equipment—such as bicycles, golf clubs, and tennis rackets—has profoundly enhanced performance by improving strength, shock absorption, and overall resilience while mitigating injury risks. These advanced materials have effectively replaced traditional options, including wood and leather, enabling the creation of user-specific designs characterised by superior strength-to-weight ratios and exceptional durability [16]. This evolution highlights the increasing reliance on high-performance composite materials in contemporary sports engineering. Currently, applications of FRPs within the sports and leisure sector account for 8.8% of the global FRP market, which is valued at approximately USD 3.5 billion.

Market analysts predict considerable expansion over the next decade, driven by the growing demand for these materials across a diverse array of sports applications [17,18]. In the Australian context, the rapid growth of the sports industry is further amplified by preparations for the 2032 Brisbane Olympics. This event is intensifying the demand for advanced sports equipment and infrastructure, fostering a heightened emphasis on the adoption of FRPs. These composites are increasingly favoured for their ability to deliver superior performance characteristics, aligning with the evolving requirements of high-quality sports goods and infrastructure.

Defence and Space Partners:

Traditional steel armour plating has been scrutinised due to its considerable weight and limited flexibility in high-performance defence applications. In contrast, fibre-reinforced polymers (FRPs) have emerged as highly sought-after materials in the defence and space sectors, offering distinct advantages in durability, weight reduction, and environmental resistance. Their widespread adoption across various military and paramilitary applications underscores their effectiveness in protecting personnel and assets from both environmental and ballistic threats.

A prominent application of FRP in defence is the development of high-grade FRP shelters, specifically designed for deployment in extreme high-altitude environments. Constructed from superior-quality FRP materials, these shelters ensure optimal insulation and climate control, even under the harshest external conditions. The integration of polyurethane (PU) foam insulation within FRP panels enhances thermal efficiency, maintaining an internal temperature of 20°C even when external temperatures plummet to -50°C. This feature makes FRP shelters invaluable for military personnel operating in remote, freezing terrains. Furthermore, the FRP panels used in defence applications possess the ability to withstand wind speeds of up to 150 km/h, support snow loads of up to 2 metres, and bear uniformly distributed floor loads of 200 kg/m² [19]. Their lightweight nature facilitates easy transportation and enables rapid assembly through a unique panel-tracking system. Even semi-skilled workers can efficiently erect these shelters with minimal training, making them a practical solution for rapid deployment in military operations, thereby further enhancing the application of FRPs in this sector [20].

Fibre-reinforced polymers are increasingly used in the aerospace sector, driven by the industry's focus on reducing mass and enhancing damage tolerance. These properties are critical for improving aircraft performance, particularly in terms of energy efficiency and manufacturing economics [21]. By significantly reducing the overall weight of aircraft, FRPs contribute to lower fuel consumption, thereby reducing operational costs. For example, the use of glass fibre-reinforced polymers instead of traditional metal materials has been shown to reduce aircraft weight by as much as 50%, resulting in a 20% reduction in overall costs, including fuel consumption [22]. In addition to weight reduction, the use of FRPs in aerospace offers significant benefits in terms of durability [23].

Composites exhibit superior resistance to fatigue and fractures from the repeated stresses of take-off and landing cycles compared to metals. This improved resilience decreases the frequency of inspections and maintenance costs over the aircraft's lifespan. Initially, carbon fibre composites were used primarily for secondary structures such as spoilers, trim tabs, rudders, and doors [24].

However, advances in manufacturing techniques and the increasing demand for materials with enhanced properties have enabled composites to replace traditional metals like aluminium, nickel, and titanium in primary structures for critical components, such as fuselages, vertical tails, rudders, empennage boxes, and wings [25]. The adoption of FRP composites in aerospace continues to increase, as evidenced by their significant presence in modern aircraft. For instance, the Boeing 787 incorporates 50% composite materials, while the Airbus A350 uses 52% [26].

Energy Partners:

Fibre-reinforced polymers play a critical role in the renewable energy sector, particularly in wind energy, as the world transitions toward low-carbon energy sources. In Australia, wind energy is a major contributor to renewable power, generating enough electricity to meet 7.1% of the nation's total demand [27]. According to the latest GenCost report, renewables—primarily driven by wind and solar energy—continue to be Australia's most cost-effective option for new-build electricity generation [28]. Additionally, based on data provided by the Australian National Science Agency, CSIRO, the average cost of wind energy is AUD 116 per megawatt-hour (MWh) now, with projections suggesting a decrease to AUD 45-78 per MWh by 2040 [29].

The adoption of renewable energy not only reduces household expenses but also contributes significantly to mitigating global warming, with the potential to cut greenhouse gas emissions by approximately 7,100 tonnes annually [30]. The electricity and energy sector is the largest contributor to Australia's emissions, accounting for 35% of the total, surpassing all other sectors. This fact shows the critical importance of transitioning to cleaner energy sources. In response to this, the Australian Government has set a target to achieve 82% renewable electricity by 2030. As of 2023, the share of electricity generated from renewable sources within the National Electricity Market (NEM) stood at an average of 39% [31]. In wind turbine manufacturing, FRP is extensively utilised in turbine blades due to its high strength, lightweight nature, and resistance to weathering.

These properties are essential for ensuring quality and cost-effective solutions that align with the growing trend of wind energy in Australia. The lightweight nature of FRP minimises energy loss caused by the self-weight of turbine components, enabling a more efficient conversion of wind's kinetic energy into electricity. Additionally, it supports the development of larger turbines capable of harnessing greater amounts of energy, thereby enhancing the overall efficiency and capacity of wind power systems.

Vehicles and EV Partners:

In the transportation sector, fibre-reinforced polymer materials have a profound impact on the automotive industry by offering lightweight alternatives that improve fuel efficiency and reduce greenhouse gas emissions [32]. Carbon fibre, in particular, is prized for its superior strength-to-weight ratio, enabling the production of lighter vehicles without compromising safety. The use of carbon fibre-reinforced polymer in automotive applications has been exemplified by innovations like the CFRP MonoCell tub, which has been pivotal in enhancing race car performance, achieving new speed records and protecting the driver [33]. The adoption of CFRP is also expanding in vehicles designed for everyday use. Automakers, including BMW, Mercedes-Benz, and Lamborghini, have increasingly integrated carbon fibre-reinforced plastics into their production lines. This growing trend is supported by optimistic forecasts for the carbon fibre market, which is projected to grow at an annual rate of 13% over the next several years [34]. Leading manufacturers, such as Toray, have identified automotive applications as a strategic priority, aligning their product development to meet the surging demand for lightweight, high-performance materials [35].

All Other Sectors with Different Industry Focus

Beyond the ACMCRC industry partner base, FRPs are utilised across various other sectors, which could potentially become future ACMCRC partners or serve as the basis for further collaboration between current partners in the development of new products, such as the marine sector.

Fibre-reinforced polymers have established a significant presence in marine industries due to their exceptional strength in specific directions and resistance to corrosion. This is particularly important in environments such as seawater, where the high concentration of chloride ions accelerates the corrosion of traditional materials like steel [36]. By strategically orienting the fibres, FRPs can provide strength in any desired direction, addressing issues such as steel corrosion, cracking, and spalling in marine applications.

The adoption of FRP in this sector began with the 1985 report from the Composite Structures Committee under the International Ship and Offshore Structures Congress (ISSC), which provided designers with the necessary information to integrate composite materials into marine structures, including ship hulls and deckhouses [37]. This paved the way for the broader use of FRPs in marine applications.

As the use of marine composites continues to expand, there has been a growing understanding of key factors such as stress limits, durability, lifespan, failure modes, fracture toughness, fire resistance, and environmental influences [36]. This research has contributed to the refinement of FRP design processes, ensuring that they meet the stringent requirements of the marine industry. FRP-based products used in this sector include CFRP moulded grating reinforced mesh, offshore drilling and production risers, GFRP/CFRP offshore deck members, submarine pipeline reinforced bars, and marine vessels, all of which highlight the material's versatility and importance in marine applications [38].

Additionally, FRPs have proven effective in rehabilitating and reinforcing structures exposed to aggressive conditions, such as bridges and piles in areas with high moisture or corrosive elements. For instance, the Allen Creek Bridge utilised FRP to repair corroded piles in a creek with aggressive waters.

Two types of FRP systems were tested: one used bi-directional wrapping applied in dry conditions, while the other involved a pre-preg system activated by water. The process took 30 to 45 minutes per pile, significantly accelerating the repair procedure. Similarly, at the Friendship Trails Bridge, FRP was employed to repair corroded piles in deeper waters. A modular scaffolding system facilitated the wrapping process, which involved two FRP systems: a pre-preg system with water-activated resin and a wet-layup system with resins that cure underwater. The Gandy Bridge also saw FRP wrapping applied to its damaged piles [39].

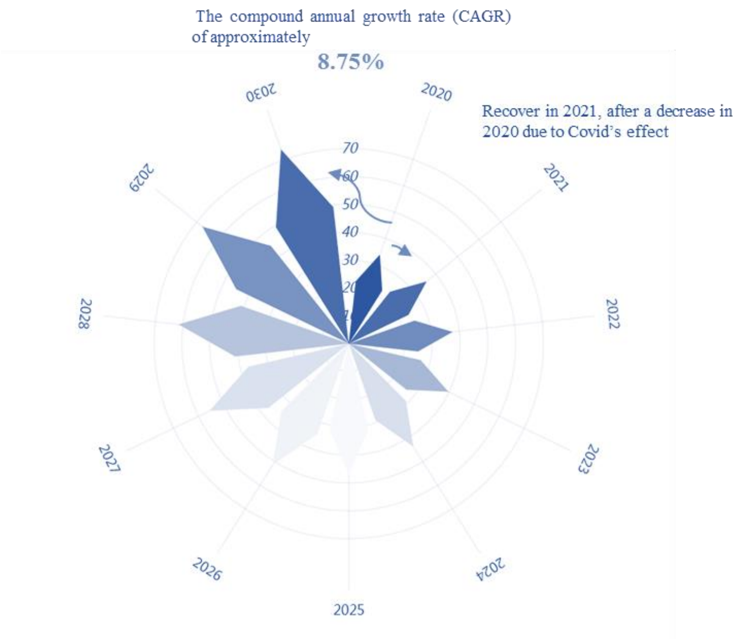
The expansion of FRP across industries is accompanied by significant challenges related to wastes generated during the manufacturing phase and end-of-life disposal and recycling, as these materials are inherently difficult to process due to their complex composition [40]. Consequently, FRP waste management has emerged as a critical focus for policymakers, researchers, and industries committed to advancing sustainable practices.

Developing and implementing innovative recycling technologies—including mechanical grinding, chemical treatments, repurposing etc.—has become essential to mitigating the environmental impacts associated with FRP waste [41-43]. These approaches not only address the pressing issue of landfill disposal but also contribute to establishing a circular economy for composite materials. If successfully scaled and refined, these recycling solutions hold the potential to significantly reduce FRP's environmental footprint, enabling its continued growth across industries while aligning with the sustainability goals of the United Nations [44].

Global Fibre-Reinforced Polymer (FRP) Market Overview: Asia-Pacific Region at the Forefront of Market Leadership

The global FRP market has experienced substantial growth, with a notable increase in market value in recent years. In 2020, the global FRP market was valued at approximately USD 75 billion, and by 2023, this value had risen to over USD 95 billion, reflecting a compound annual growth rate (CAGR) of around 5% [45]. However, the COVID-19 pandemic, which severely disrupted production and halted manufacturing and construction activities, resulted in a temporary setback [46]. This led to a slight negative growth rate during this period, impacting supply chains and causing delays in key industrial projects. Despite these challenges, the global FRP market has rebounded and is now projected to reach approximately USD 190 billion by 2030, growing at a robust CAGR of over 7% from this point onward [45,47].

The Asia-Pacific region is the primary driver of global FRP demand, accounting for 43.59% of the global market share in 2023 and is expected to capture 58% of the market share in 2024 [47]. This dominance can be attributed to several interrelated factors, including rapid urbanisation, expanding industrial bases, and rising disposable incomes. Between 2020 and 2030, the Asia-Pacific market for FRPs is expected to grow faster, outpacing the global market CAGR by 1.15%. This forecast highlights the region's growing consumption of FRP materials, with China, India, and Japan emerging as major contributors compared to Oceania, as the key sectors driving the demand for FRP in Asia-Pacific include construction, transportation, and electronics.



China and India are two of the fastest-growing construction sectors, characterised by a surge in infrastructure projects [45,48]. The expanding middle class and rapid urbanisation are transforming cities and residential areas, increasing the demand for sustainable and durable materials. Government infrastructure investments, such as China's Belt and Road Initiative (BRI) and India's Smart Cities Mission, offer vast opportunities for FRP applications in urban infrastructure and transportation networks.

Japan remains a key player in the transportation sector, where the advanced automotive and aerospace industries heavily utilise FRP in vehicle production. The Japanese government's focus on sustainability, including initiatives to promote hydrogen-powered and electric vehicles, further stimulates the demand for FRP.

In the electronics sector, India is witnessing significant expansion, driven by both domestic consumption and exports. The country's growing electronics market, supported by rising incomes, an expanding middle class, and increasing smartphone penetration, has led to a greater need for high-performance materials that are lightweight, durable, and thermally efficient, consequently boosting demand for FRPs.

Oceania, while exhibiting moderate growth compared with other regions in Asia-Pacific, benefits from niche, high-value applications, particularly in renewable energy and infrastructure sectors [49]. There is also a noticeable increase in the demand for FRPs in the wind energy and sports industries [50].

North America and Europe: Mature Markets with High Potential

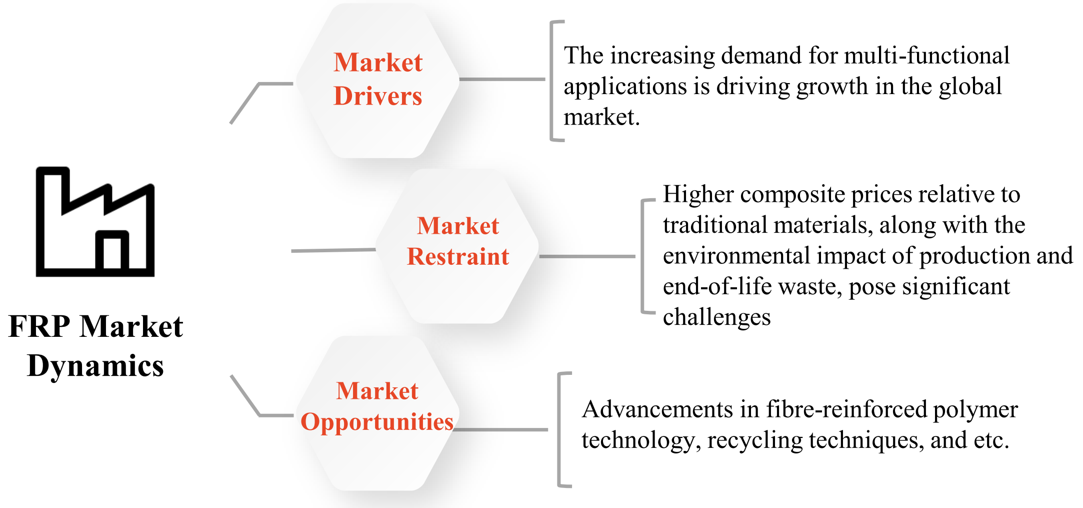
North America, with the United States as a major contributor, is expected to see continued growth in the FRP market, particularly driven by advancements in aerospace, automotive, and renewable energy sectors [51,52]. The U.S. automotive industry's shift towards electric vehicles (EVs) and the increasing demand for lightweight, high-performance materials continue to drive the demand for FRPs, especially carbon fibre-reinforced polymers (CFRPs), which are essential in achieving energy efficiency goals for electric vehicles. Additionally, aerospace companies in the U.S. are increasingly integrating FRPs into aircraft construction to enhance fuel efficiency and reduce maintenance costs [45,53].

In Europe, the market is growing at a moderate CAGR of 4.50% [54]. The European Union's commitment to reducing carbon emissions and increasing renewable energy production is fostering demand for FRP materials, particularly in the manufacturing of wind turbine blades. Glass fibre-reinforced polymers (GFRPs) are extensively used in this sector due to their light weight, durability, and cost-effectiveness. Moreover, the European automotive sector is shifting towards lightweight FRP composites to reduce vehicle weight and improve fuel efficiency, in alignment with stringent environmental regulations.

Other Regions: Emerging Opportunities

South America and Africa exhibit lower growth rates but remain critical emerging markets for FRP, as industrialisation and economic development continue to unfold. South America, with its expanding construction and renewable energy sectors, presents growing opportunities, particularly in Brazil and Argentina. Africa's growth is slower, but rising demand for infrastructure and housing offers potential for FRP materials in construction projects [45].

Global Market Dynamics: Sectoral Distribution, Emerging Trends, Innovative Techniques, and Future Outlook

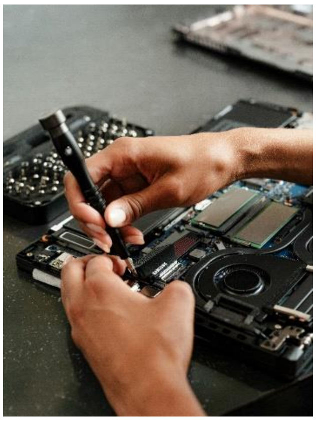


The global FRP market is characterised by a wide range of applications, with significant contributions from key sectors such as transportation, construction, electronics, and sports and leisure. As of 2023, the transportation sector alone accounts for 37.9% of the global FRP market share, followed closely by the construction sector at 28.9%. Electronics and sports and leisure contribute 18.1% and 8.8%, respectively, with other industries comprising the remaining share [47].

In the transportation sector, FRP plays a critical role in automotive, aerospace, and marine applications. In 2022, the global automotive industry produced over 85 million vehicles, reflecting an approximate 6% growth compared to 2021 (80 million units). The increasing demand for lightweight components to enhance fuel efficiency and reduce emissions is a key driver for the use of FRPs in automotive manufacturing. In aerospace, CFRPs are employed in airframe and interior applications to reduce weight and improve fuel efficiency, directly aligning with stringent regulatory requirements for lowering emissions.

The construction sector is another major application area for FRPs, owing to the materials' durability and resistance to environmental wear. These properties are especially crucial in regions prone to natural disasters such as earthquakes, floods, and hurricanes. In the Asia-Pacific region, the rapid pace of infrastructure development, including residential, commercial, and public sector projects, sustains strong demand for glass fibre reinforced due to their excellent durability, corrosion resistance, and cost-effectiveness.

The electronics sector also plays a significant role, accounting for 18.1% of the global FRP market share. The demand for FRPs in electronics is driven by the need for lightweight, high-strength materials for modern devices such as smartphones, laptops, and wearables. Additionally, FRPs' exceptional electrical insulation properties make them valuable in electronic components, power generation, and distribution systems. As technological advancements continue to drive innovation in the electronics industry, the role of FRPs is expected to expand further.



While the sports and leisure sector represents a smaller portion of the market at 8.8%, it shows considerable promise. FRP materials are used in high-performance equipment such as bicycles, sports cars, and recreational gear. The adaptability of FRPs to various product types, combined with their strength and lightweight properties, makes them ideal for these applications, particularly with the increasing demand for eco-friendly, high-performance and luxury products in the sports industry.

However, the market faces several challenges that could hinder its continued expansion. These challenges include the high cost of raw materials, particularly carbon fibres, the complexities and environmental impacts associated with recycling FRP materials. Industry stakeholders must adapt and innovate to overcome these barriers and ensure the market's sustainable growth.

One of the most pressing challenges is the cost of raw materials. Carbon fibre, a key component in many high-performance FRP applications, is expensive due to the high energy requirements and specialised processes needed for their production [55]. This issue significantly impacts industries such as automotive manufacturing, where the demand for lightweight, high-strength materials is substantial. Despite this, major manufacturers like Teijin Limited, Toray Industries Inc., Solvay, and Mitsubishi Chemical Carbon Fibre and Composites Inc. are investing heavily in research and development to reduce these costs. These efforts focus on innovating production technologies as well as improving recycled fibre performance to make remanufactured products more cost-competitive across a broader range of applications.

However, achieving meaningful reductions in cost remains a formidable challenge, particularly for smaller businesses that may lack the financial resources to invest in such high-tech solutions. Alongside material costs, there is increasing pressure to develop effective methods for recycling FRP materials as part of global sustainability efforts. As composite waste continues to accumulate, the need for efficient recycling solutions becomes more urgent. Currently, the recycling of composite materials is costly and technically complex, often requiring harsh treatments that can damage the fibres, diminishing their economic value.

The inefficiency of current recycling methods is a significant barrier to the widespread adoption of recycled FRP materials, especially in high-performance applications where preserving fibre integrity is essential. Consequently, research is intensifying to develop more effective, cost-efficient recycling technologies that maintain fibre properties and reduce environmental impact. Given the growing consumption of FRPs, particularly in emerging markets, this issue is likely to worsen unless scalable recycling methods are implemented. Although recycling technologies are advancing, they remain far from ideal.

In response to the environmental concerns surrounding FRP waste, a new approach has been proposed: several researchers are exploring the integration of natural fibres into polymer matrices to create more eco-friendly composite materials [56]. Hybrid composites, which combine natural fibres such as flax, kenaf, or hemp with synthetic fibres like carbon or glass, offer a promising alternative to traditional FRP materials. These materials generally have lower environmental footprints due to the renewable nature of natural fibres, and they can enhance the mechanical properties of composites, making them more versatile for various applications. For instance, a bicycle frame made from a composite material containing 70% flax fibre and 30% carbon fibre is both lighter and more durable than traditional metal frames, offering enhanced damping properties ideal for high-performance sports equipment [57].

Similarly, hybrid composites made from kenaf and glass fibres exhibit superior mechanical strength and rain erosion resistance, making them suitable for aerospace applications [58]. These case studies show that natural fibres can be successfully incorporated into high-performance FRP applications, addressing cost and sustainability concerns. However, while hybrid materials show promise, they face challenges related to consistent performance and scalability. Although renewable, natural fibres can vary in quality and may not always offer the same level of mechanical performance as synthetic fibres, complicating large-scale and cheaper production.

Looking ahead, advancements in natural fibre-based composites are likely to transform the industry, provided these materials are standardised, particularly as companies and consumers increasingly prioritise sustainability. However, the future of the FRP market will still mainly depend on the continued development of more efficient recycling technologies and the evolution of manufacturing processes that reduce material waste. If these challenges are addressed effectively, the FRP market has the potential to continue its growth, expanding into emerging markets and contributing to the development of more sustainable industries.

Scope and Objectives of the Study

Market Analysis and Industry Appetite: This report will investigate the current market demand and industry appetite for recycling FRP composites in Australia. It will analyse the economic, regulatory, and environmental factors driving the need for sustainable FRP recycling solutions and identify potential end-users and their unmet needs within the Australian industry.

Usage and Recycling Statistics: This report will investigate the current usage of FRP composites in Australia and assess how much of these materials are being recycled, ending up in landfills, or incinerated. It will compare these statistics with global trends to establish a baseline for improvement.

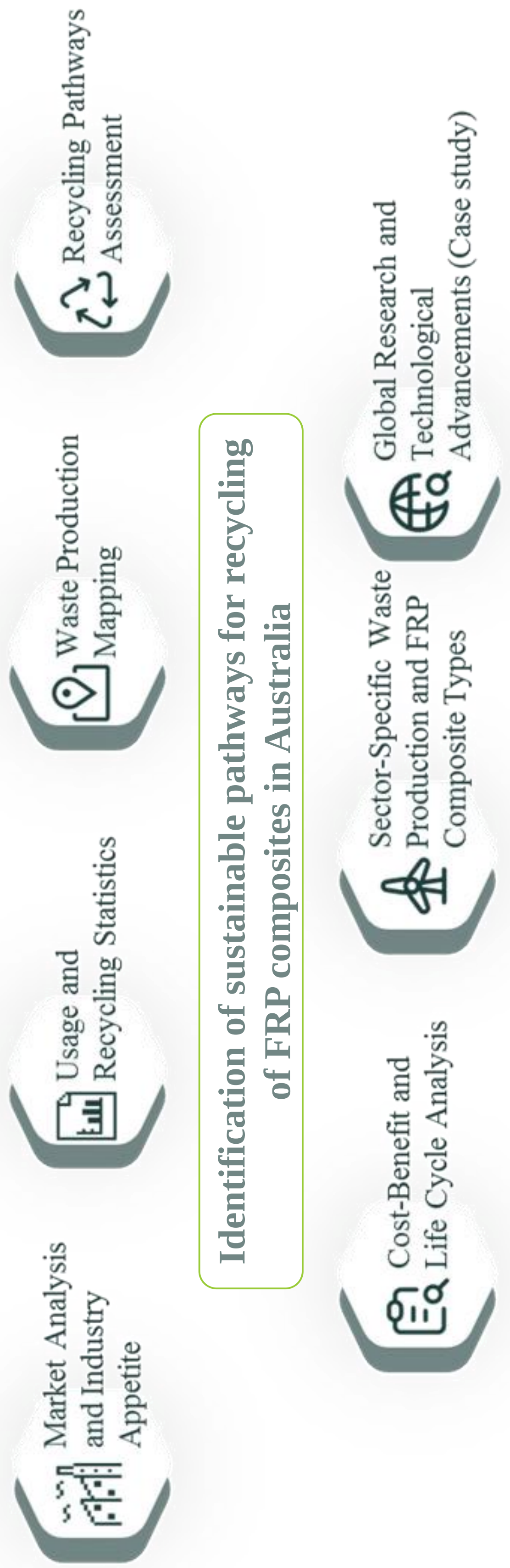
Waste Production Mapping: We will quantify FRP waste production from diverse composite industries across different Australian states. The report will develop a comprehensive understanding of the spatial distribution of FRP waste generation to guide effective recycling strategies and will identify regional variations in waste generation patterns.

Recycling Pathways Assessment: We will evaluate the existing FRP recycling pathways in Australia and their implications for the environment and industry partners. The report will identify technological gaps, logistic challenges, and the readiness of current methods.

Cost-Benefit and Life Cycle Analysis: A rigorous cost-benefit analysis of potential FRP recycling approaches will be performed and the environmental and economic impacts of different methods through life cycle analysis will be calculated, aiming to identify the most sustainable options.

Sector-Specific Waste Production and FRP Composite Types: The report will analyse waste production in key sectors such as renewable energy, car manufacturing, construction, aerospace, marine, leisure and sport industries to prioritise sectors for recycling interventions. It will examine different types of FRP composites, including Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP), as well as various manufacturing techniques (e.g., wet-lay up, pultrusion, pre-preg, resin infusion). It will help to understand the unique challenges associated with recycling each type and technique.

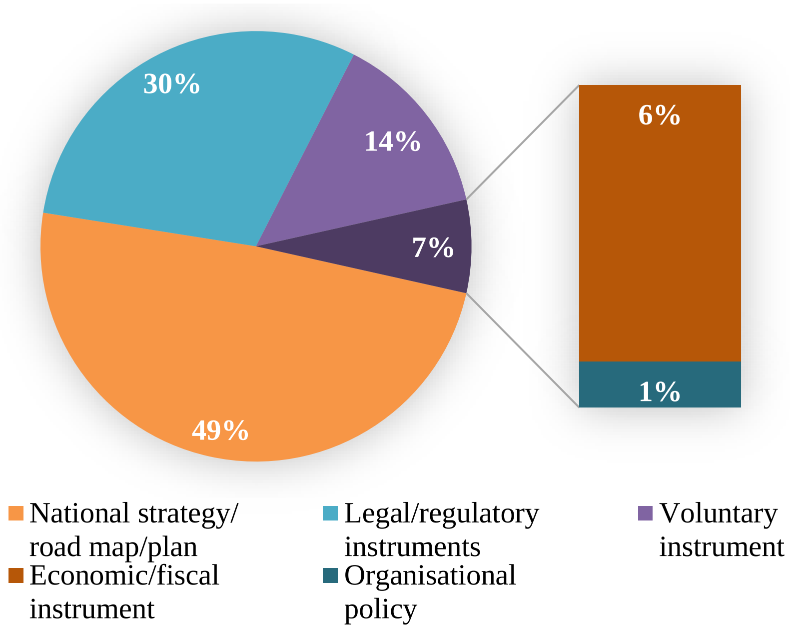
Global Research and Technological Advancements: We will investigate research and technological advancements in FRP recycling from regions like the European Union (EU), the United States of America (USA), and Asia. It will finally draw insights and best practices to inform Australian industry solutions.


Identification of sustainable pathways for recycling of FRP composites in Australia
Market Analysis and Industry Appetite
Usage and Recycling Statistics
Waste Production Mapping
Recycling Pathways Assessment
Cost-Benefit and Life Cycle Analysis
Sector-Specific Waste Production and FRP Composite Types
Global Research and Technological Advancements (Case study)

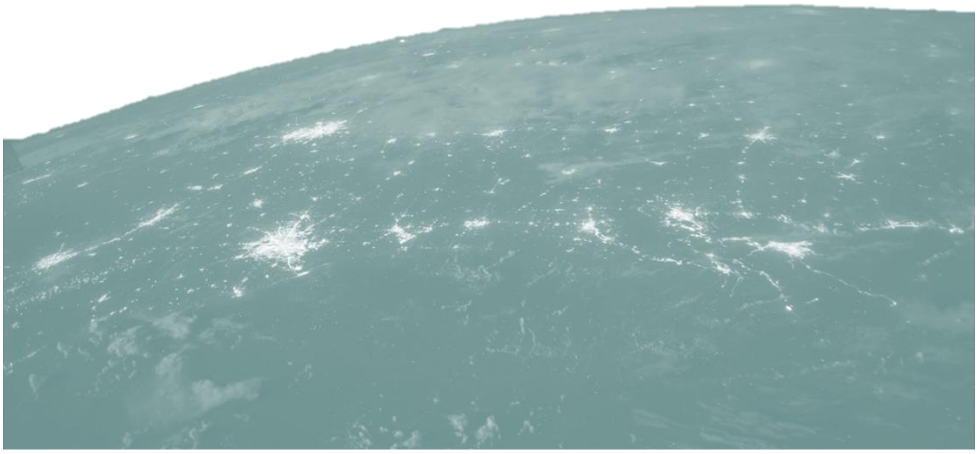
Section 2: Designing for Sustainability

Sustainable Development: Shaping the Future of Global Innovation and Growth through Composite Waste Management

The Agenda for Sustainable Development is committed to fostering balanced development across all nations, integrating economic, social, and environmental dimensions. As highlighted in the Sustainable Development Goals Report 2024, there has been a notable increase in the number of countries and companies reporting on their sustainability efforts [59]. In the realm of composite materials, achieving sustainability extends beyond improving production costs and process management. Effective waste management has become a critical focus, particularly concerning social responsibility and reducing environmental impact. This issue is particularly relevant in industries relying on materials such as fibre-reinforced polymers (FRPs), which present significant challenges in recycling and waste disposal. The following sections will explore the sustainability initiatives undertaken by three key regions—Asia, Europe, and North America—examining their strategies, successes, and ongoing challenges in advancing more sustainable practices in composite materials.



Policy Instruments Supporting the Shift to Sustainable Consumption and Production by Type: 2023 (Percentage)



Europe

Europe is at the forefront of advancing sustainable development within the composite materials sector, addressing the significant challenges associated with glass fibre-reinforced plastics and carbon fibre-reinforced plastics. These materials present substantial recycling difficulties, particularly in industries such as wind energy, automotive, aerospace, and construction. As demand for composites continues to grow, so too does the need for efficient, scalable, and environmentally sustainable recycling solutions. In response, Europe has initiated several innovative projects and developed a range of technologies to facilitate the recycling of composite materials, contributing to the circular economy and mitigating environmental impacts [60].

One of the leading technologies for managing composite waste in Europe is co-processing in cement kilns, exemplified by Finland's KiMuRa system [61,62]. This approach involves shredding composite waste—such as decommissioned wind turbine blades and boat hulls—and processing it alongside raw materials in cement production. Co-processing offers dual benefits: it reduces the reliance on fossil fuels and virgin materials in cement manufacturing, while simultaneously diverting composite waste from landfills. Studies indicate that this method results in a reduction of CO_2 emissions by approximately 335 kg per tonne of composite material processed, compared to traditional cement production methods. Furthermore, co-processing offers a more sustainable alternative to incineration, which produces considerably higher CO_2 emissions (496 kg per tonne). The scalability of the KiMuRa system is evident, with around 30 companies across various sectors already adopting co-processing for composite waste management, highlighting its effectiveness and potential for broader application [60,63].

Another significant advancement in composite recycling within Europe is the implementation of Digital Product Passports (DPP). The Joint Industrial Data Exchange Platform (JIDEP) is leading efforts to integrate DPPs across industries [60,64]. This initiative enables the digital tracking of materials and products throughout their lifecycle, ensuring that composite materials are recycled in a way that preserves their value. DPPs provide detailed information on the composition, environmental impact, and end-of-life considerations of a product, facilitating better management of composite materials at the end of their life cycle [65,66]. This system is particularly advantageous in industries such as wind energy, automotive, and aerospace, where large volumes of composites are produced and disposed of. The integration of DPPs enables the more efficient separation of composite components during recycling, ensuring that recovered materials can be reused optimally and sustainably. This digital transparency aligns with Europe's broader goal of transitioning to a circular economy, reducing waste, and promoting resource efficiency [67].

Wind turbine blades, one of the most challenging composite waste streams due to their size, material complexity, and high decommissioning rates, have driven substantial advancements in recycling technologies. European initiatives, such as the REWIND project, focus on improving the recyclability of wind turbine blades through the exploration of pyrolysis and solvolysis methods [60,68,69]. Pyrolysis, a thermal process that decomposes composite materials in an oxygen-deprived environment, facilitates the separation of resin from reinforcing fibres [1,70]. The REWIND project seeks to optimise this process by reducing its time and temperature requirements, and enhancing its energy efficiency. Additionally, the REFRESH Horizon Europe project investigates the use of thermoplastic binders and cleavable epoxies, which enable easier separation of the resin from fibres, thereby improving recyclability and ensuring that the recovered materials meet the necessary quality standards for reuse in manufacturing new products. Furthermore, the wind related project explores the use of reactive thermoplastics in turbine blades, which offer greater recyclability than traditional thermoset composites [71]. These initiatives underscore Europe's commitment to finding scalable, energy-efficient solutions for managing wind turbine blade waste, with a focus on reducing the environmental footprint of composite materials in the renewable energy sector [60].

Chemical recycling technologies are emerging as a promising method for breaking down composite materials [72]. The Multi-level Circular Process Chain for Carbon and Glass Fibre Composites project, for example, focuses on developing chemical processes to recycle carbon fibre composites, converting them into high-value products [73]. These chemical processes, coupled with spectroscopic sorting technologies, enable more precise identification and separation of composite materials based on their chemical composition. This targeted approach enhances the efficiency of recycling processes, ensuring that the recovered materials meet the necessary standards for reuse in high-performance applications. The integration of chemical recycling and advanced sorting techniques is critical for improving the quality and yield of recycled composite materials, enabling their continued use in demanding sectors such as aerospace and automotive [74-76].

In parallel with thermal and chemical recycling processes, bio-based composite materials are gaining traction in Europe as part of a broader initiative to promote sustainable and recyclable materials. The FURHY project exemplifies this trend, focusing on the development of bio-based epoxy resins that offer improved recyclability over conventional thermoset resins [77]. By combining these resins with natural fibres, such as hemp, and recycled carbon fibres, bio-based composites provide a more sustainable alternative to traditional materials. These composites are not only renewable but also more easily recyclable, avoiding the complex chemical structures that typically hinder the processing of conventional thermoset resins. The use of renewable resources in composite production represents a significant step toward reducing the environmental impact of the composite industry and offers a viable solution that aligns with the principles of a circular economy [78,79]. However, bio-based epoxy resins, which utilise plant-based rather than petroleum-based solvents, often face challenges related to durability and mechanical strength when compared to traditional petroleum-based resins. Some biocomposites exhibit higher moisture uptake at saturation levels due to their lower hydrophobicity and greater porosity. This can lead to reduced mechanical stiffness and strength in wet environments [80]. To address these limitations, ongoing research is required to focus on improving the performance and durability of bio-based resins.

The automotive and aerospace sectors, which heavily rely on high-performance composites, have also made significant strides in the upcycling of prepreg waste. Initiatives such as Ricreare are addressing this issue by developing technologies to upcycle uncured prepreg scraps from the cutting process into new prepreg materials [81]. This approach reduces waste and lowers the demand for virgin prepreg materials, enhancing both the cost-effectiveness and environmental sustainability of the production process. Similarly, an initiative has been developed to create a material derived from upcycled uncured CFRP prepreg scraps, which is now used in the production of automotive components. These upcycling technologies are crucial for reducing the environmental impact of composite waste in industries where performance and material integrity are paramount.

Looking forward, the future of composite recycling in Europe is closely tied to ongoing technological innovation and increased cross-industry collaboration. Projects such as the DEECOM process in Germany, which uses superheated steam to separate resin from fibres, and the growing adoption of co-processing in cement kilns, represent scalable solutions for composite waste management [82,83]. These initiatives are essential for Europe’s broader environmental objectives, providing viable pathways for recycling composite materials while minimising waste and energy consumption. As these technologies mature, they hold the potential to set global benchmarks for composite recycling, supporting Europe as one of the main leaders in sustainable materials management.

Asia

Asia’s focus on sustainable innovation addresses critical environmental challenges while simultaneously unlocking significant market opportunities. The region’s high demand and expansive capacity for industrial operations and installations make it a prime location for advancing recycling technologies and low-carbon economies. Asia has emerged as a new star in the global sustainable development of the composite materials market, particularly in recyclable materials, advanced recycling processes, and waste management solutions. The region’s innovative strategies to address pressing environmental challenges, such as carbon emissions and composite waste, are exemplified by multiple successful case studies.

An example of this progress is demonstrated through recyclable thermosetting resin products, such as EzCiclo thermosetting resin, which enables the complete degradation and recycling of components at the end of their service life. Complementing this innovation is Swancor's proprietary CleaVER recycling technology, which transforms waste materials into recycled fibre and oligomer, offering a fully circular solution to thermoset composite challenges [60,84,85]. This technology has been successfully implemented by Siemens Gamesa for large-scale turbine blade production, demonstrating its industrial feasibility [86]. Beyond wind energy, its applications extend to the marine and automotive sectors, recreational vehicles, and carbon fibre bicycle frames, underscoring its versatility and alignment with low-carbon objectives.

Similarly, significant strides have been made in overcoming the technical challenges of scaling recycled carbon fibre (rCF) production for industrial use. For instance, innovative "rice grain" short-cut rCF, derived from T800 fibre reclaimed from Boeing 787 aircraft waste, features high packing density, excellent feedability, and superior bonding with polymer matrices. These attributes have facilitated its adoption in components for UAV brands and a mass-produced new energy vehicle model, marking a pivotal step toward kiloton-scale industrial applications. Additionally, the use of rCF products has diversified into 3D printing filaments and laptop shells, offering a sustainable alternative to high-content, long glass fibre-reinforced resins and lightweight alloys. These advancements position rCF as a viable and environmentally friendly material for various industries.

To address the growing carbon fibre waste from the wind energy sector, advanced recycling technologies have also been developed. Third-generation systems, including pyrolysis single-furnace recovery and large-scale continuous pyrolysis production lines, are capable of processing up to 1,000 tonnes of carbon fibre composite waste annually, producing 600 tonnes of regenerated carbon fibre. This regenerated material is utilised in wastewater treatment adsorption, carbon fibre surface felt production, and carbon fibre paper manufacturing. By employing advanced sizing agents such as PA, PU, and PP, the mechanical properties and adhesion of recycled fibres have been enhanced, offering a cost-effective alternative to virgin carbon fibre. With wind turbine blades contributing an estimated 62,000 tonnes of unused carbon fibre annually, such innovations are critical for mitigating future waste, projected to escalate to 483,000 tonnes by 2035 [60].

North America

Similar developments have occurred in North America, where the emphasis on advancing sustainable practices in composite recycling has spurred significant innovation and collaboration across industries, particularly in the transportation, aerospace, and energy sectors. Partnerships between major players, such as Hexcel, Carbon Conversions, and Fairmat, highlight the potential of collaborative efforts in addressing the environmental challenges posed by composite material waste.

Hexcel, a leading manufacturer of lightweight composites for the aerospace and transportation industries, has initiated several recycling collaborations aimed at diverting composite waste from landfills. In partnership with Carbon Conversions and Fairmat, Hexcel has developed a system to reclaim dry carbon fibre and prepreg waste from its manufacturing processes [87,88]. These materials are then converted into value-added second-life products, such as chopped fibres, nonwovens, and cured carbon composite components. This collaboration has yielded significant results, with Hexcel and Fairmat successfully diverting over 170 tonnes of prepreg material from waste in 2023 alone [89]. By 2030, they aim to achieve a 30% reduction in waste sent to landfill [90]. This outcome demonstrates the scalability and effectiveness of these recycling initiatives, underscoring their potential to reduce waste in high-value sectors that rely heavily on carbon fibre composites.

Beyond ongoing efforts, several North American companies are advancing composite recycling technologies. One example is a patented carbon fibre recycling process that recovers fibres with mechanical properties comparable to virgin material. These recycled fibres are utilised in various applications, including chopped fibres, thermoplastic pellets, and 3D printing filaments. This approach not only diverts carbon fibre waste from landfills but also improves the material's cost-effectiveness and accessibility for new applications. By enhancing the recyclability of carbon fibre, such advancements contribute significantly to reducing the environmental impact of industries dependent on high-performance materials [91].

Similarly, a closed-loop, zero-waste manufacturing process using reclaimed carbon fibres has been pioneered, significantly advancing the efficiency and commercial viability of carbon fibre recycling. The development of 3D preforming technology has played a key role in achieving these improvements. The Composite Recycling Technology Centre (CRTC), located at the Port of Port Angeles, is dedicated to carbon fibre remanufacturing. The CRTC processes surplus carbon fibre and transforms it into new products, diverting approximately 1,800 tonnes of carbon fibre scrap that would otherwise be disposed of in Washington state landfills each year [92]. This facility plays a crucial role in supporting a circular economy while serving as a model for sustainable manufacturing practices in the composites industry [93].

In addition to its efforts in carbon fibre recycling, Carbon Rivers is making significant efforts in recycling glass fibres, particularly those from decommissioned wind turbine blades. This process, supported by the U.S. Department of Energy, enables the recovery of 99.9% pure glass fibres, which are then repurposed into new products [94]. By effectively creating a circular economy within the wind energy sector, Carbon Rivers is addressing a major environmental challenge faced by the renewable energy industry—the disposal of decommissioned turbine blades, which are primarily made from composite materials that are notoriously difficult to recycle.

These innovations reflect a broader trend in North America, where the emphasis is increasingly on multi-faceted approaches to handling end-of-life composite materials and reusing all recycled products. Several companies are at the forefront of developing scalable, cost-effective technologies that divert composite materials from landfills, giving them a second life. By improving the recyclability of these materials, North American companies are not only reducing the environmental impact of these industries but also alleviating the pressure caused by local fibre shortages.

Why Sustainable Practices Are Essential for the Australian Composites Market

The integration of sustainable practices in the Australian composites market is increasingly recognised as crucial for achieving long-term environmental and economic resilience. Kerryn Caulfield, Executive Director of Composites Australia, emphasised the critical role fibre-reinforced polymers (FRPs) play in advancing green infrastructure, particularly under extreme conditions where their durability and reliability are unmatched [95]. These materials, essential to various industries, are poised to contribute significantly to environmentally sustainable applications, provided that manufacturing and recycling practices are aligned with contemporary sustainability standards.

Globally, heightened environmental concerns and stringent regulatory frameworks are pushing industries towards adopting eco-friendly production and waste management processes. The composites sector is no exception, as its reliance on resource-intensive materials poses unique challenges. Sustainable practices are pivotal for reducing the environmental footprint of composite manufacturing, extending product lifespans, and improving recyclability. These efforts align closely with Australia's national sustainability goals and national waste policy action plan, including the transition to a circular economy that prioritises resource efficiency and waste minimisation [96,97]. The waste hierarchy serves as a foundational framework in this endeavour (Figure 1), emphasising the sequential priorities of waste avoidance, resource recovery, and environmentally responsible disposal [96,98]. Established under the Waste Avoidance and Resource Recovery Act 2001, this hierarchy guides policies and practices aimed at efficient resource use while minimising environmental harm.

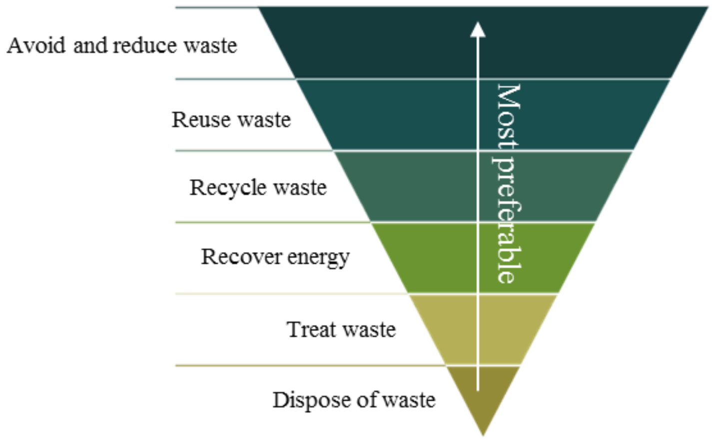
The NSW Waste and Sustainable Materials Strategy 2041, for example, outlines a 20-year vision for reducing waste and rethinking how the economy produces, consumes, and recycles materials [99]. This strategy aligns with the Net Zero Plan Stage 1: 2020–2030, which targets achieving net zero emissions from organic waste to landfill by 2030 [100]. In addition, hazardous waste tracking systems have been introduced to streamline national consistency in waste management, supporting the goals of the National Waste Policy Action Plan. Other states have also implemented similar regulations and provided recommendations to ensure sustainable practices benefit Australia’s growing advanced materials market. These efforts demonstrate a collective national commitment to integrating sustainability into industry operations, fostering a robust framework for long-term growth and environmental stewardship.

Local companies are responding to these regulatory developments by embedding sustainability into their operations, with some emerging as leaders in the field. Composite Australia, a member of the Global Composites Sustainability Coalition, has adopted a comprehensive approach to ecological sustainability. The company’s ethos reflects a deep commitment to conserving natural resources, minimising environmental and health impacts, and integrating long-term sustainability into its product design, manufacturing processes, and resource management strategies. Importantly, it also emphasises the necessity of fostering a sustainability mindset [101]. Also, Carbon Revolution integrates recycled composite materials into its lightweight carbon fibre wheels. These advanced wheels not only outperform traditional aluminium counterparts in weight and durability but also significantly reduce emissions and enhance vehicle efficiency. Through collaborations with research partners, Carbon Revolution has quantified the environmental benefits of its designs, showcasing how recycled materials can align cutting-edge performance with ecological responsibility [102].

The Australian composites market, however, faces challenges in fully realising its sustainability potential in the aspect of continuous innovation in technology and waste management. While there has been progress in developing innovative recycling technologies, the commercialisation and widespread implementation of these methods remain limited. Collaborative efforts between industry and academia are essential to addressing these gaps, as partnerships can drive advancements in waste treatment technologies and improve the efficiency of recycling processes. Such collaboration is particularly critical in a market that has yet to fully capitalise on the opportunities presented by a circular economy.

For example, improved recycling techniques and the adoption of eco-friendly materials, developed through collaborative research, can be seamlessly transferred to industry via well-structured communication platforms. These platforms can facilitate effective partnerships between researchers and industry stakeholders, enabling the composites sector to achieve greater resource efficiency while significantly reducing its overall environmental impact. Such synergies are essential for addressing the pressing challenges of sustainability and ensuring the practical application of innovative technologies across diverse industrial contexts.

The advancement of sustainable practices within the composites industry mirrors broader trends in Australia's evolving advanced materials sector. Regulatory frameworks across multiple states are increasingly designed not only to achieve ambitious environmental goals but also to bolster the global competitiveness of Australian companies. Sustainable manufacturing has evolved from being a mere trend to becoming an essential element of modern industry. Through the integration of cutting-edge materials, renewable energy sources, and more efficient production techniques, Australian businesses are positioning themselves at the forefront of global sustainability initiatives.



What's Next for Australia? Learn from Global Trends, Contribute to Global Solutions: Strategies for Innovation, Policy Alignment, and Stakeholder Engagement in the Australian FRP Industry

Australia's increasing recognition of the need for sustainable practices in composite materials aligns with its national sustainability objectives and the transition towards a circular economy. Drawing on global case studies, Australia is well positioned to establish local applications. To shape the future of global innovation and growth through composite waste management, the country could focus on several key strategies:

1. **Technology Transfer and Innovation:**

Collaborating with global leaders in composite recycling technologies will enable Australia to adopt and adapt these innovations to meet local needs. For instance, Australia could benefit from adopting Europe's technological advancements, ensuring their scalability and integration into existing regulatory frameworks. Notably, co-processing in cement kilns presents a promising solution for managing composite waste, particularly in regions with significant cement production. Additionally, the adoption of Digital Product Passports could enhance transparency across the lifecycle of composite materials, thereby supporting resource recovery and recycling, especially in industries such as wind energy and aerospace. Australia's composite sector may also gain from Asia's innovations in thermoset recycling and carbon fibre recovery. With the increasing demand for composites in infrastructure projects and the automotive sector, the application of similar recycling technologies could reduce the environmental footprint of Australia's composites market. Furthermore, involvement in the global composites supply chain, particularly in the aerospace and automotive industries, could benefit from advanced carbon fibre recycling methods, which would reduce both production costs and waste disposal.

2. **Policy Alignment and Industry Incentives:**

Australia's regulatory frameworks provide a solid foundation for integrating circular economy principles. However, strengthening policies that encourage innovation in recycling and waste management, alongside incentives for businesses to adopt sustainable practices, will accelerate the widespread adoption of these approaches.

3. **Industry Education and Stakeholder Engagement:**

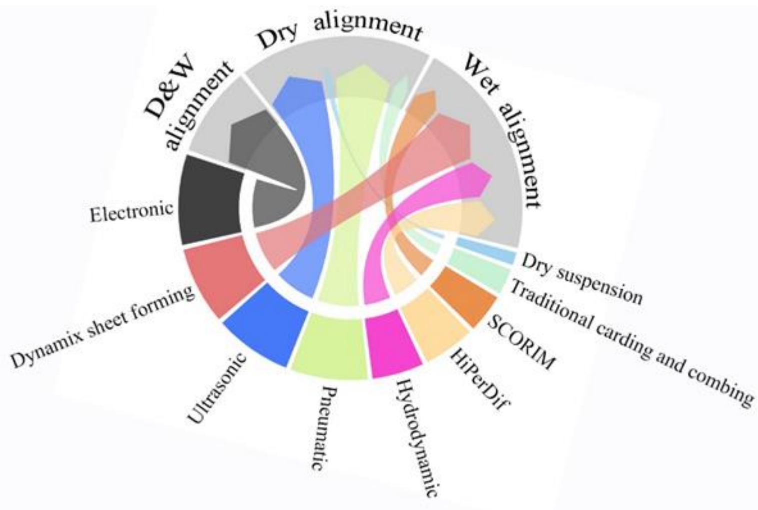
Fostering a sustainability mindset within Australia's composite materials industry is crucial. North America's emphasis on collaboration between industry leaders and innovators highlights the significance of partnerships in advancing composite recycling technologies. Similarly, Australia could benefit from fostering collaborative efforts between research institutions, industry stakeholders, and technology providers, which would accelerate the commercialisation of recycling technologies. Encouraging innovation and collaboration within the local market, along with educating stakeholders on the importance of sustainability, recycling, and resource efficiency, will drive greater collaboration and innovation. The success of the global composites market will depend on active participation from all sectors, including government, research institutions, and the private sector.

Case study 1: Closing the Loop on FRP Life Cycles with Advanced Alignment Technique

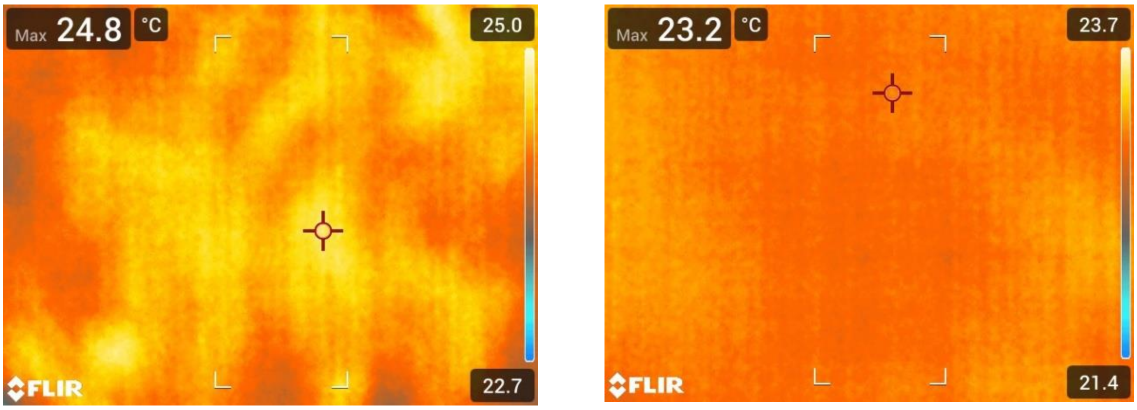
Fibres recovered from fibre-reinforced polymer (FRP) waste consistently exhibit a random arrangement, posing significant challenges to closing the life cycle of CFRP and achieving sustainable development for FRP materials. Given the substantial influence of fibre orientation on the mechanical properties of CFRP produced with recycled short fibres, various fibre alignment techniques have emerged over recent decades.

Researchers from the University of Sydney conducted a comparative analysis of the critical components of dry and wet alignment techniques. Using a systematic approach that integrates the Analytical Hierarchy Process and Fuzzy Comprehensive Evaluation methodologies, they evaluated the effectiveness of different techniques in realigning recycled fibres [103]. The findings indicate that the hydrodynamic approach offers superior fibre alignment and increased efficiency. However, this method presents several challenges, including uneven mat thickness, lower productivity, and complexities in fibre collection and drying processes.

To address these limitations, researchers from the University of Sydney developed a patented alignment equipment [104] employing an innovative approach to enhance hydrodynamic alignment by optimising fibre dispersion, alignment channels, and fibre collection processes. Scaling up and modifying the prototype equipment achieved alignment rates of 88% within 30 degrees and 77% within 15 degrees. Additionally, the fibre mat produced using this method attained a high utilisation rate of nearly 81%, ensuring uniform thickness across the directly produced recycled fibre mat.



Aligned fibre mat



(a) (b)

Comparison between the thermographic scanning of fibre mats produced by using carding and combing (a) and hydrodynamic alignment methods (b)

Case Study 2: Recyclable Schiff Base Composites for Enhanced FRP Recyclability

Researchers from Deakin University are working on the development of recyclable thermosetting polymers, which could serve as a key case study in advancing the circular economy for Carbon Fibre Reinforced Polymer composites. A novel Schiff base CFRP composite has been synthesized using a multifunctional monomer derived from vanillin, a renewable biosource material, and phosphonitrilic chloride trimer [105]. This Schiff base polymer demonstrates excellent mechanical properties, with tensile and flexural strengths of 461 and 455 MPa, respectively, and a high glass transition temperature (Tg) of 129 °C.

In addition to its outstanding mechanical performance, the Schiff base CFRP exhibits remarkable repairability, retaining up to 70% of its original flexural strength after multiple repairs. A key advantage of this material is its inherent fire retardancy, with a UL94 V0 rating, thanks to the phosphorus/nitrogen rings in its structure. Furthermore, the CFRP composite can be chemically recycled under mild conditions at room temperature, enabling the reclamation of clean carbon fibres without compromising their mechanical properties.

This work introduces a promising solution for the sustainable manufacture of CFRP composites by combining recyclable thermoset chemistry with high-performance material properties. The Schiff base CFRP offers a closed-loop recycling process, eliminating the need for additional fire-retardant additives and providing a sustainable, cradle-to-cradle approach for the future of carbon fibre composites.

Adopting Circular Economy Principles for Composite Materials in Australian SMEs

The Department of Climate Change, Energy, the Environment and Water defines it as "a way of achieving sustainable consumption and production, as well as nature-positive outcomes." To advance these goals, Australia’s environment ministers are committed to collaborating with the private sector, fostering a circular pathway through initiatives such as the Circular Economy Ministerial Advisory Group, which provides critical advice on opportunities, challenges, and actionable strategies to achieve substantial improvements by 2030.

CSIRO, Australia’s National Science Agency, underscores the urgency of transitioning from the current linear economic model—characterised by the “take-make-dispose” paradigm—to a circular model. Such an approach addresses global challenges, including climate change, biodiversity loss, waste, and pollution.

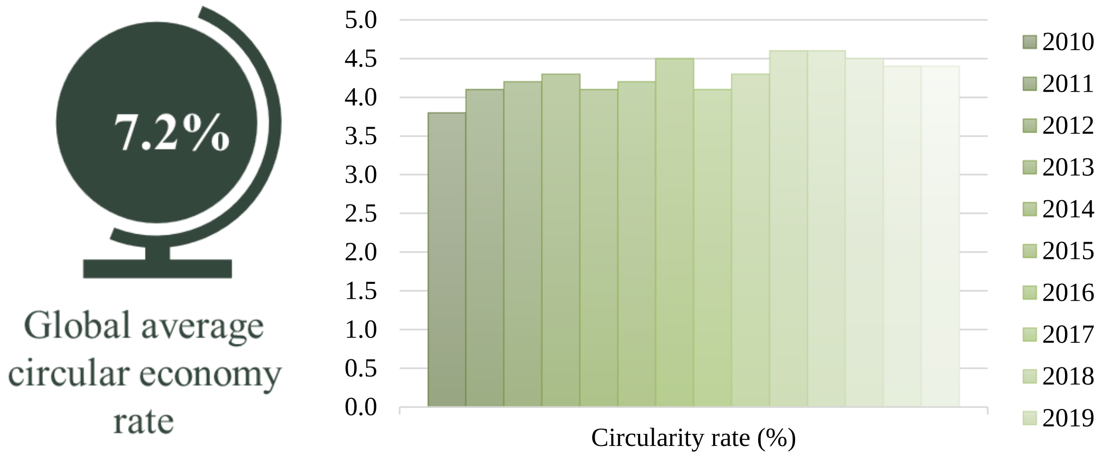
Australia’s circular economy rate, at 4.4%, remains significantly below the global average of 7.2%, according to the Australian Bureau of Statistics. Enhancing circularity is critical, as Australia's material productivity has increased modestly, rising from $1.45 AUD/kg in 2010 to $1.58 AUD/kg today [106]. However, the nation’s material footprint per capita, at 31.0 tonnes, indicates considerable room for improvement. Although a slight upward trend in the circularity rate has been observed since 2010, substantial efforts are needed to accelerate this progress. Closing this gap presents substantial economic opportunities, with estimates suggesting a potential $210 billion economic boost by 2050 [107].

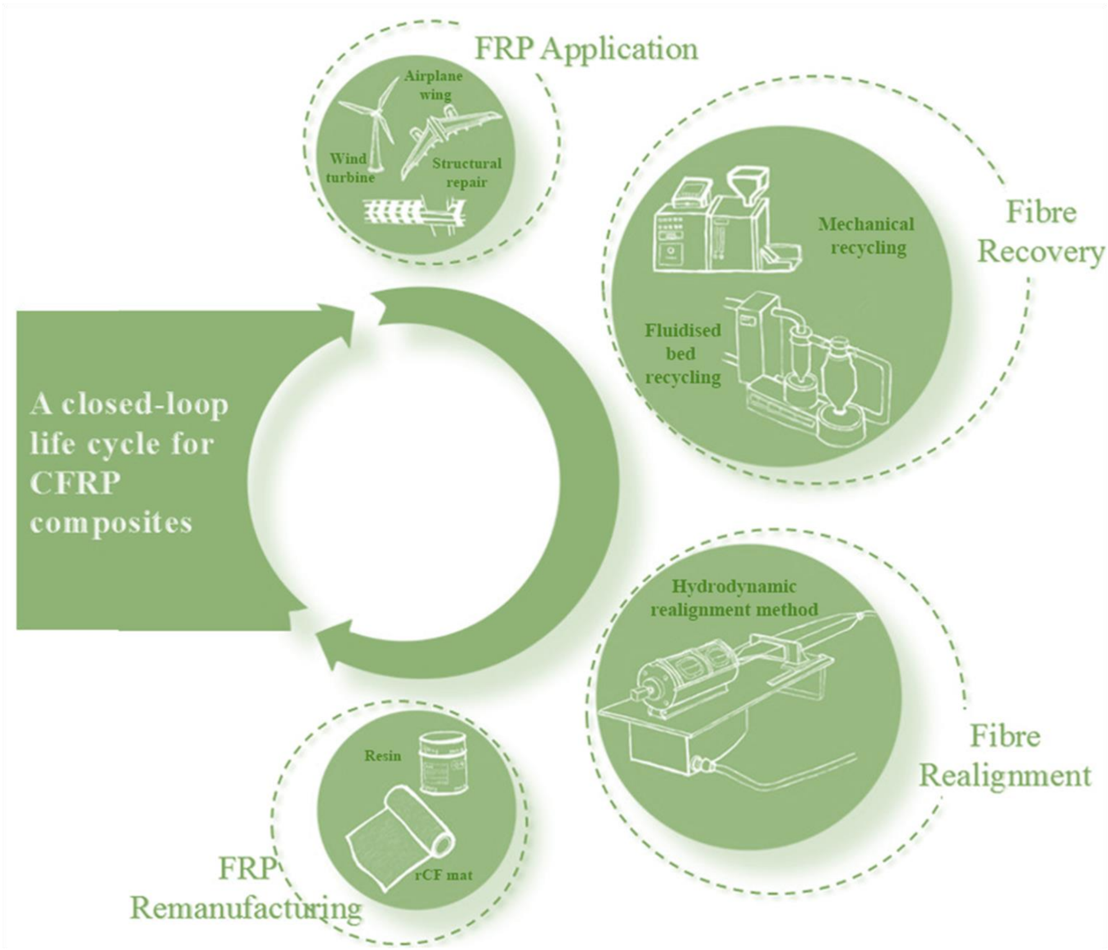
To support this transition, the government is actively pursuing research pathways aimed at reducing per capita waste generation by 10% and achieving an 80% resource recovery rate across all waste streams by 2030, guided by the waste hierarchy [97]. The CSIRO’s report, prepared in collaboration with Australia's Chief Scientist, highlights the waste management and resource recovery sector as a critical area for improvement. It emphasises the importance of consistent governance, fostering a zero-waste culture, and market development as foundational elements. Investments, such as the $250 million Recycling Modernisation Fund, which leverages over $1 billion in total investments, are expected to accelerate the development of this sector into a competitive advantage [108].

Small and medium enterprises (SMEs) are key players in driving CE adoption in Australia. Research by Ayon Chakraborty reveals that Australian SMEs view CE adoption as instrumental to sustainable development [109]. However, significant barriers remain, including the absence of well-defined business processes. While SMEs recognise the potential for sustainability gains through CE practices, many lack the requisite knowledge and strategies to implement these changes effectively.

Previous works [110] emphasise the importance of achieving a closed-loop life cycle for fibre-reinforced polymer (FRP) composites. Establishing such a system is essential for reducing industrial pollution while enhancing material and energy efficiency for the circular economy path. To realise this closed-loop cycle, fibre recovery systems must address four critical aspects: application, fibre recovery processes, alignment of recycled fibres, and remanufacture [111].

Moreover, the research highlights the influence of consumer pressure on Australian SMEs to adopt CE principles [112,113]. To advance a circular economy within FRP manufacturing, it is vital to consider the perspectives and demands of end-users. This involves linking FRP recycling initiatives to the practical applications of recycled materials, ensuring cost efficiency, and minimising environmental impacts. Understanding composite end user sectors' demand for driving meaningful progress toward a sustainable and circular economy.





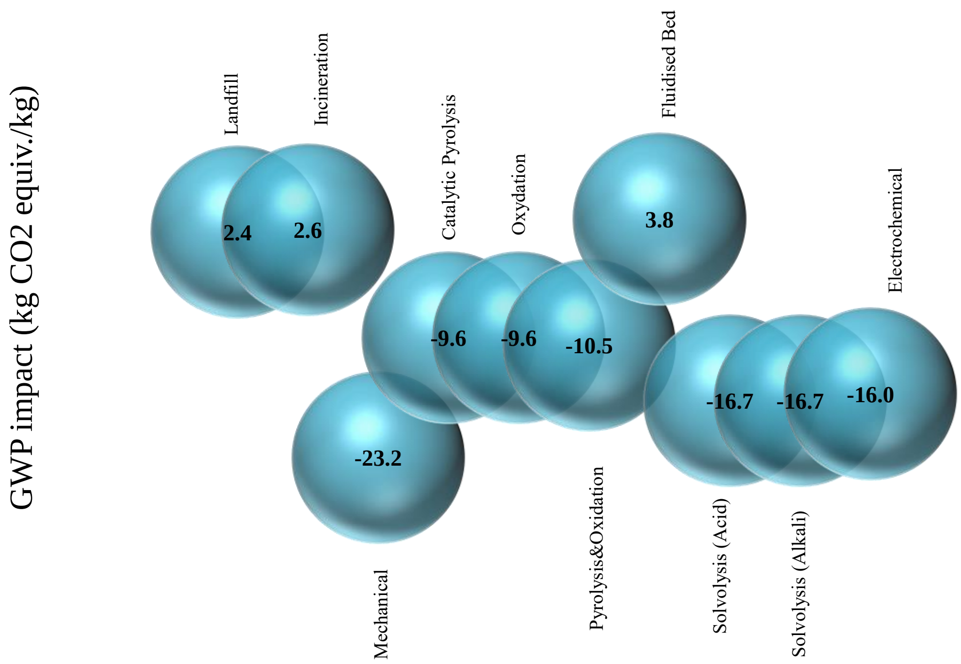
The Impact of Different FRP Recycling Methods: Advancing Health and Environmental Sustainability

Global warming impact:

Assessing the global warming potential (GWP) of CFRP recycling methods is crucial for evaluating their environmental impacts. GWP measures the heat absorption potential of various greenhouse gases relative to carbon dioxide (CO_2), serving as a reference metric. Recycling processes with lower GWP values are considered more environmentally favourable, while negative GWP values signify a net reduction in atmospheric greenhouse gases.

Traditional disposal methods, such as landfilling and incineration, significantly exacerbate environmental issues by generating substantial greenhouse gas (GHG) emissions. Conversely, several recycling methods, including solvolysis and hybrid thermal techniques, demonstrate relatively low GWP values, effectively balancing material recovery with reduced emissions. Thermal recycling methods for CFRP, such as pyrolysis and catalytic oxidation, release emissions like carbon monoxide, CO_2, and aromatic compounds, particularly at high temperatures. However, research shows that these emissions stabilise when recycling processes are conducted at temperatures below a certain value, where most reactions conclude.

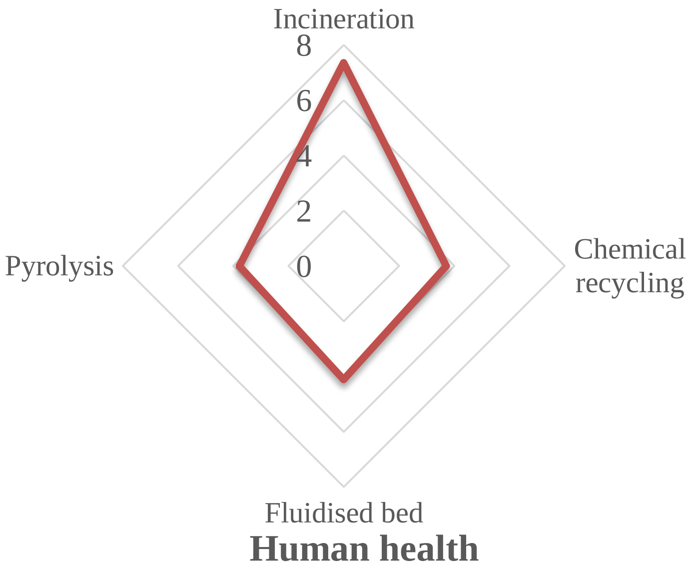
This temperature constraint helps minimise CO_2 emissions, aligning these methods with environmental sustainability objectives. Nevertheless, certain thermal processes, such as fluidised bed recycling, exhibit higher GWP values due to the energy-intensive nature of their operations and greater emissions, highlighting their contribution to global warming. These findings underscore the importance of selecting and optimising recycling methods to mitigate their environmental impact while ensuring efficient material recovery.

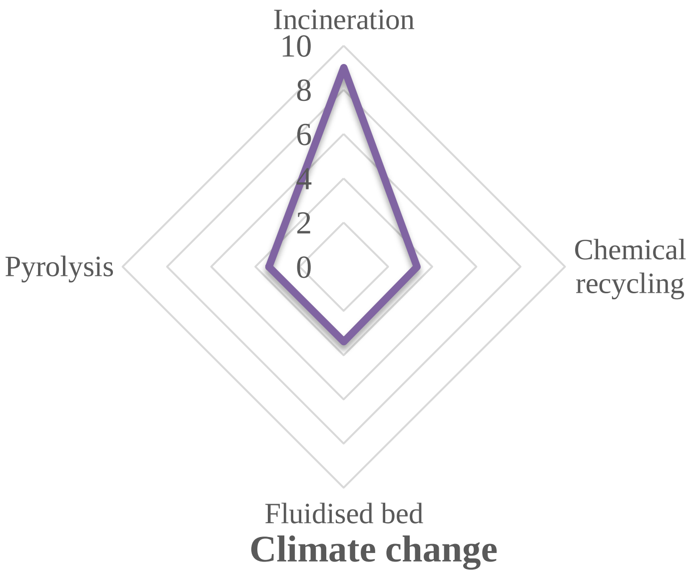


Human Health and Climate Change Impacts:

Incineration, which serves as the baseline for comparison, has significant adverse health effects due to the release of hazardous emissions. It can pose serious health risks through the release of leachate, which can contaminate surrounding ecosystems and water sources. In contrast, chemical recycling demonstrates a much lower human health impact, approximately 50% less than landfilling. This reduction in health risks is largely attributed to the closed-loop systems used in chemical recycling, which limit exposure to harmful by-products and prevent the release of toxic substances into the environment. Pyrolysis and fluidised bed recycling, though somewhat more impactful than chemical recycling, still offer around a 45% reduction in negative impacts on human health compared to landfilling.

In terms of climate change, chemical recycling significantly outperforms traditional methods, with its impact on climate change being approximately two-thirds lower than landfilling. Pyrolysis and fluidised bed recycling also show notable improvements, reducing climate change impacts by about 62% compared to landfilling. These advanced recycling techniques offer substantial reductions in greenhouse gas emissions, demonstrating their potential as more environmentally sustainable alternatives to traditional waste disposal practices.



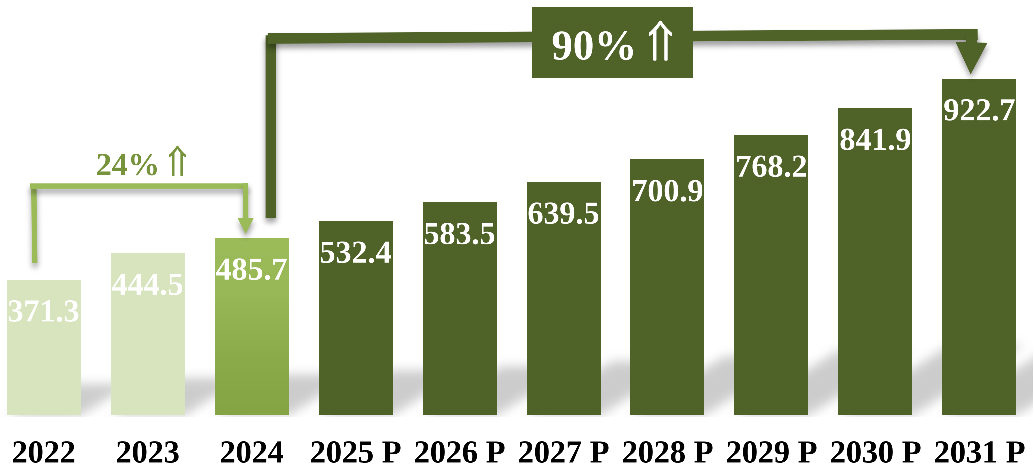


Section 3: Global and Asia-Pacific FRP Recycling Market Analysis

Global FRP Recycling Market Overview

The global Fibre-Reinforced Polymer (FRP) recycling market is experiencing strong growth. According to recent market reports and available statistics, the market was valued at $371 million in 2022 and expanded to $444 million in 2023, reflecting a significant year-on-year increase of 19.7% as the sector recovered post-COVID. This positive trend is expected to continue, with projections indicating the market will reach $486 million this year.

By 2025, the market is forecasted to grow further to $532 million. Looking beyond 2025, the market is set to sustain robust growth, with a compound annual growth rate (CAGR) of 9.6% from 2024 to 2031. The market is projected to increase to $639 million within three years and is expected to reach $842 million by 2030. This upward trajectory underscores the growing importance of sustainable practices in the composites sector, driven by regulatory frameworks, technological advancements, and the increasing adoption of FRP materials across a wide range of industries. The following section will provide an in-depth examination of the market dynamics, key drivers, and potential challenges within the FRP recycling space.



Global FRP Recycling Market ($ million)

Uncovering the Key Drivers and Growth Opportunities of Global FRP Recycling Market

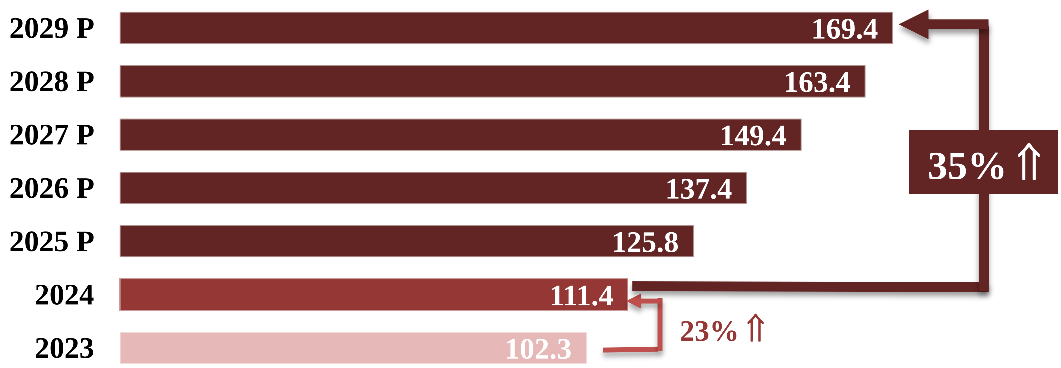
The development of the fibre-reinforced polymer (FRP) recycling market is intricately shaped by a combination of external and internal drivers. These drivers significantly influence the direction of recycling practices, technological advancements, and industry growth. Four key factors stand out: (1) the growing volume of accumulated FRP waste; (2) public demand and regulatory pressures regarding landfill diversion and waste management; (3) local fibre supply constraints; and (4) the transition towards sustainability and a circular economy.

The first two drivers are external forces, largely shaped by global policy and public demand, while the last two represent internal forces, influenced by the operational realities of specific markets and localised conditions. Together, the aforementioned four drivers form the foundation of a dynamic and rapidly evolving market, with significant implications for industry stakeholders globally.

1. **The Growing Volume of FRP Waste: Addressing the Rising Challenge**

The volume of FRP waste globally is on a notable upward trajectory, reflecting the broader growth in FRP production and consumption across key industries such as construction, automotive, aerospace, and electronics. As these sectors continue to expand, the amount of FRP waste is expected to rise significantly. In 2023, the global FRP waste volume was recorded at 102.3 kilo tonnes. This volume is forecasted to increase to 111.4 kilo tonnes in 2024, marking an increase of 8.1%. The Compound Annual Growth Rate (CAGR) for global FRP waste between 2024 and 2029 is calculated at approximately 10.34%. By 2025, this figure is expected to rise to 123 kilo tonnes, continuing a steady climb. After 3 years, it is expected to increase to 150 kilo tonnes and after 5 years, this figure is expected to reach 183 kilo tonnes. This represents a 78.6% increase in global FRP waste over the period from 2023 to 2029.

This upward trend is driven by the increasing use of FRP materials, which are often preferred for their high strength-to-weight ratios and durability across various applications. However, the growing volume of waste presents a critical challenge for industries, as the need for efficient recycling technologies becomes more pressing. Manufacturing technologies that focus on minimising waste during production, such as advanced cutting, trimming, and shaping techniques, are essential for addressing waste generation at the source. In parallel, the development of cost-effective and high-capacity recycling methods will be crucial in managing the increasing volume of FRP waste efficiently and sustainably.



Global FRP Wastes (kilo tonnes)

2. **Public Demand and Regulatory Pressures: A Push for Sustainable Waste Management**

Public demand for more sustainable waste management practices has risen in tandem with increasing regulatory pressures worldwide. Governments in various countries are implementing stricter waste management regulations to address the environmental impacts of FRP waste. For example, in the UK, despite the production of 110,000 tonnes of composite materials annually, only 15% of these materials are recycled at the end of their lifecycle. Similarly, in the United States, only 10% of FRP materials are recycled, with the majority being sent to landfills or incinerated.

This situation is unsustainable, both environmentally and economically, leading to calls for more effective recycling solutions. As public awareness of environmental issues increases, governments worldwide are intensifying efforts to manage FRP waste more effectively. Regulatory pressures are acting as a catalyst for the adoption of innovative recycling technologies, with a growing emphasis on reducing the environmental impact of FRP materials through recycling and material recovery.

The UK government has taken significant steps to address these challenges through legislation, such as the 2021 Environment Act, which sets a legislative target to halve the amount of residual waste sent to landfill and incineration by 2042, compared to 2019 levels.

Furthermore, the European Union’s Landfill Directive aims to limit the landfilling of recyclable waste by 2030, with the goal of reducing municipal waste sent to landfills to 10% by 2035. These legislative measures reflect an increasing focus on reducing landfill waste, and incineration is also being reconsidered as an environmentally responsible waste management method.

Similarly, China’s Circular Economy Promotion Law stresses the importance of recycling and resource utilisation. The law advocates for reducing waste through recycling, reuse, and resource recovery, encouraging production safety and preventing secondary pollution. It underscores the importance of involving various governmental levels and agencies in the implementation and supervision of circular economy practices.

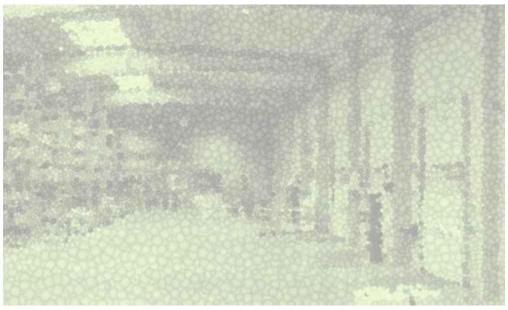
Australia, too, has made strides in this area with its National Waste Policy Action Plan, which includes ambitious targets such as reducing waste generation by 10% per person by 2030 and achieving an 80% recovery rate from all waste streams. These regulations are becoming the driving force behind the push for improved recycling technologies and the diversion of FRP waste from landfills and incineration.

3. **Local Fibre Supply Constraints: Addressing Market Vulnerabilities**

Another key internal driver influencing the FRP recycling market is the issue of local fibre supply constraints. The global carbon fibre market, which plays a crucial role in FRP production, has been experiencing substantial growth. In 2023, the global demand for carbon fibres was approximately 117,500 tonnes, with a steady annual growth rate of 8.68%. However, this growth is compounded by challenges related to local fibre production, particularly in countries like Australia.

Australia, in particular, is heavily reliant on imports for its carbon fibre supply, sourcing materials from countries such as the US, Japan, China, and Europe. This reliance on external suppliers has made the country vulnerable to global trade disruptions, highlighting the need for greater self-sufficiency in carbon fibre production. Australian companies have made efforts to address this issue. For example, a report published by Composite Australia shows Colan Australia emerging as the famous local manufacturer of carbon fibre textiles. The company has been producing carbon fibre products for over 30 years, but its capabilities remain limited in terms of meeting the future needs of carbon fibre fabricators. Additionally, GMS Composites, another Australian firm, is involved in pre-impregnating carbon fibres with resin, yet the market still relies heavily on imports.

Therefore, the challenge of local fibre supply constraints in Australia has sparked a growing interest in developing more efficient recycling methods that could recover high-quality fibres from end-of-life products. By recovering valuable fibres from waste FRP products, the FRP industry can reduce its reliance on virgin materials, mitigating the impact of supply shortages and contributing to the long-term sustainability of the sector.



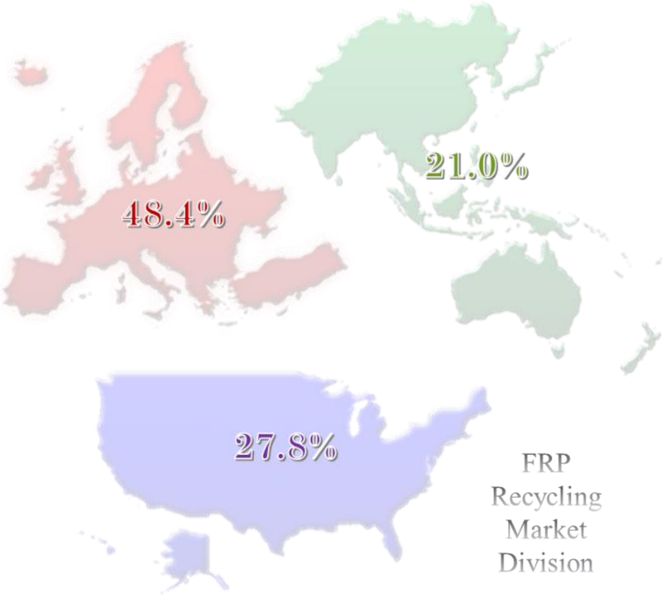
4. **Sustainability and the Circular Economy: Advancing Technological Innovations**

The fourth key driver in the FRP recycling market is the shift towards sustainability, particularly the adoption of circular economy principles. This approach encourages the reuse, recycling, and regeneration of materials throughout their lifecycle, rather than relying on a linear “take-make-dispose” model. The circular economy is not only about waste reduction but also about creating new value from materials that would otherwise be discarded.

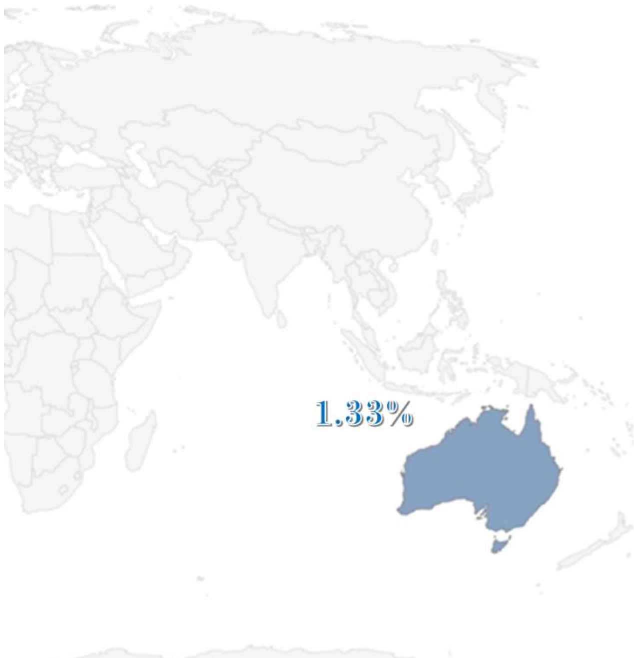
Challenges and Strains in the Asia-Pacific FRP Recycling Market: Impact on Growth and Development

The Asia-Pacific region, while being the leading consumer of Fibre-Reinforced Polymers across industries such as construction, transportation, and electronics, faces significant challenges in its FRP recycling market due to economic inefficiencies and technological limitations [14]. In contrast, regions like Europe and North America are making more progressive strides in their recycling efforts. Europe, which holds a leading market share of 48.4%, began focusing on the sustainable development of FRP materials earlier than other regions. North America, currently the second-largest market at 27.8%, is projected to experience the fastest growth in the future.

Both regions have made substantial investments in research and development for FRP recycling technologies, resulting in more efficient and cost-effective recycling processes and driving greater sustainability in their FRP industries. Given these disparities, Asia-Pacific faces an urgent need to enhance its recycling capabilities. As FRP consumption continues to rise in the region, both governments and industries may need to prioritise research and development to close the technological and economic gaps.



In 2023, Australia's FRP recycling market accounted for approximately 1.33% of the global market share, which equates to a value of approximately USD 3.2 million. This relatively small but growing segment highlights the significance of embracing sustainable practices and recycling composite materials. With a projected compound annual growth rate (CAGR) of 6.7% from 2024 to 2030, Australia's FRP recycling market is expected to see a steady expansion, reaching an estimated market value of USD 9.3 million by 2030. Despite this positive growth trajectory, the market's size remains limited compared to leading markets like China and Japan. Consequently, Australia's recycling infrastructure for FRPs is still in the early stages of development. The country will need to invest significantly in research, technological innovation, and collaborative efforts among producers, end users, recyclers, and academia to scale up its recycling capabilities effectively.

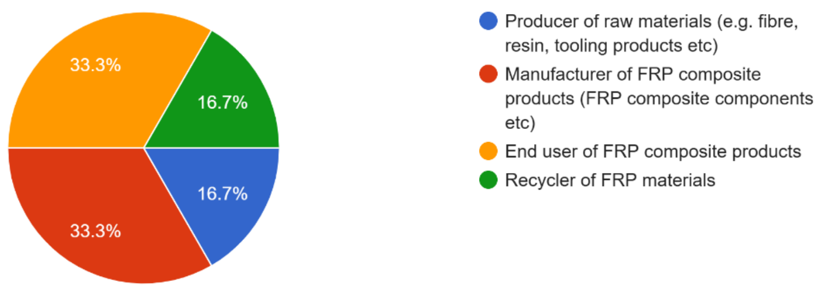


Shaping the Australian FRP Market: Analysing Dynamics, Recycling Challenges and Opportunities, and Demand Insights Through Multi-Sector Surveys and Interviews

To better shape the Australian FRP market dynamics and understand the demand within the local industry, a survey was designed and circulated, as shown in the Appendix. The responses provide a comprehensive overview of FRP waste treatment and recycling practices within the Australian and New Zealand industries. The findings reveal distinct trends, challenges, and opportunities that reflect both local and global dynamics in the FRP sector. Smaller businesses in these regions exhibit a pronounced focus on domestic markets, with 50% of respondents catering primarily to local demand. Conversely, larger industries demonstrate a strong export orientation, targeting markets in Sweden, Singapore, South Korea, Canada, Germany, New Zealand, and the USA.

This underscores the critical importance of understanding and complying with diverse governmental sustainability regulations across jurisdictions. For businesses seeking global market access, familiarity with international recycling trends and sustainable practices is not only essential for market entry but also vital for maintaining long-term competitiveness in a rapidly evolving industry landscape.

Six Survey responses were collected from companies representing four major roles within the FRP industry: producers of raw materials, manufacturers of composite products, end-users, and recyclers. The distribution of roles of the responding companies in the FRP industry is shown in the following chart.

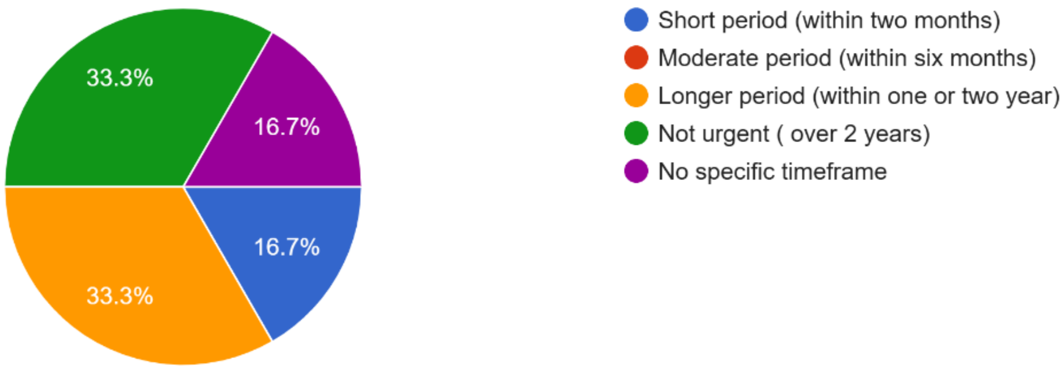


The findings provide valuable insights into the priorities and challenges faced by each group. Producers of raw materials have not incorporated recycled materials into their manufacturing processes, prioritising production quality and efficiency over sustainability. Barriers include technological constraints, insufficient expertise, and the complexity of navigating regulatory compliance. Moreover, limited customer demand for sustainable products further discourages the adoption of sustainable practices. These findings highlight the need for market education and technological innovation to enable producers to integrate recycled materials confidently without compromising product quality or profitability.

End-users, particularly those in the aerospace and renewable energy sectors, reported significant challenges in recycling and reusing FRP materials. Difficulties in separating components and retaining acceptable mechanical properties during recycling emerged as recurring themes. Notably, one respondent from the renewable energy sector described a collaborative initiative with academic researchers to develop recycling processes for fibreglass products, achieving up to 80% retention of mechanical properties. Despite such advancements, the majority of producers and end-users continue to rely on landfilling or incineration, citing ease of disposal, the operational complexity of recycling methods, and the suboptimal quality of recycled materials as primary deterrents. These practices underscore the persistent gaps in technological development and market readiness that must be addressed to drive broader adoption of sustainable solutions.

Feedback from recyclers, however, offers a more optimistic perspective. Recyclers reported that only 1–5% of FRP waste is generated per unit during the recycling process. Furthermore, some recyclers are innovatively repurposing materials, such as using wood from turbine blades as a heat source, thereby reducing energy consumption during operations. These practices demonstrate promising efforts to minimise environmental impact.

Nevertheless, a critical challenge persists: 66.7% of respondents identified the limited availability of recycling technologies as a significant obstacle to effective FRP waste management. While there is strong consensus that the proportion of recycled materials in FRP products will increase over the next five years, respondents acknowledged that this shift is likely to be gradual. Most companies view the adoption of recycled materials as a long-term strategy rather than an immediate priority, underscoring the need for sustained investment and research in eco-friendly recycling technologies to accelerate progress.



These findings emphasise that while advancements are being made, significant barriers remain. Addressing technological limitations, regulatory complexities, and market demand issues will be crucial to fostering the widespread adoption of sustainable practices in the FRP industry. By investing in innovative recycling technologies and strengthening collaborations between industry and academia, companies can better position themselves to meet future demand for sustainable FRP products and secure their place in an increasingly sustainability-driven global market.

Section 4: A Comprehensive Review of Various Recycling Methods for FRP Materials

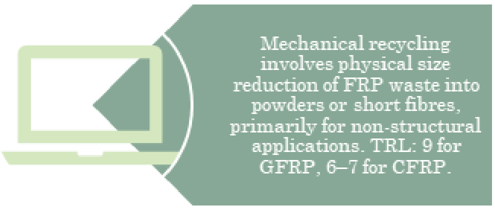
Overview of Current Recycling Techniques

The increasing demand for sustainable waste management solutions in FRP industry has driven the advancement of various recycling techniques. These methods aim to mitigate the environmental and economic challenges associated with landfilling and incineration, while enabling the recovery of valuable fibres from composite materials. However, the applicability, efficiency, and scalability of these methods differ significantly. This analysis examines the diverse FRP recycling techniques, focusing on their operational principles, strengths, limitations, and industrial readiness, with Technology Readiness Levels (TRL) serving as a framework for assessment [114].

Mechanical Recycling

Summary and TRL:

Mechanical recycling involves the physical size reduction of FRP waste into powders or short fibres, primarily for non-structural applications. TRL: **9 for GFRP, 6–7 for CFRP**.



Analysis:

Mechanical recycling has become a prevalent method due to its simplicity, low capital cost, and adaptability for various composite waste streams. The process typically involves grinding or milling, converting FRP waste into reusable materials for applications such as fillers in concrete or secondary reinforcement. However, the fibres recovered are significantly degraded in length and mechanical properties, particularly in CFRP composites, where fibre lengths are often reduced to less than 20 mm [115,116]. In GFRP recycling, mechanical methods show promise for integration with the construction industry. Studies have demonstrated that incorporating mechanically recycled GFRP into concrete mixtures can enhance compressive and tensile strength, and improve environmental performance by offsetting the use of virgin materials. Despite its industrial maturity, low economic incentives for GFRP recycling, driven by the affordability of virgin glass fibres, hinder widespread adoption [117].

Case Study 3: Leveraging Composite Recyclate as Reinforcement in Inverse-Vulcanised Polymers

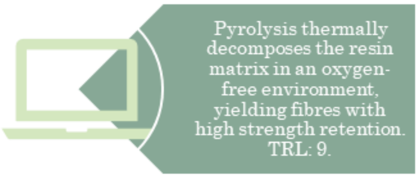
Collaboration between researchers at Deakin University and Flinders University has demonstrated how the judicious choice of mechanically recycled second-life polymers can transform reclaimed matrix-coated fibre particles into a valuable asset [118]. This approach enhances the use of largely inert polymers, enabling homogeneous dispersions of recyclate in vitrimeric polymers.

Incorporating mechanically recycled carbon fibre into a sulfur-based polymer synthesised via inverse vulcanisation was investigated. The poly(S-r-DCPD) produced in this study has been shown to exhibit vitrimeric properties. In this context, the reactivity of S-S bonds provides a potential avenue for in-service repair and recycling, further reducing composite waste.

Pyrolysis

Summary and TRL:

Pyrolysis thermally decomposes the resin matrix in an oxygen-free environment, yielding fibres with high strength retention. TRL: **9**.



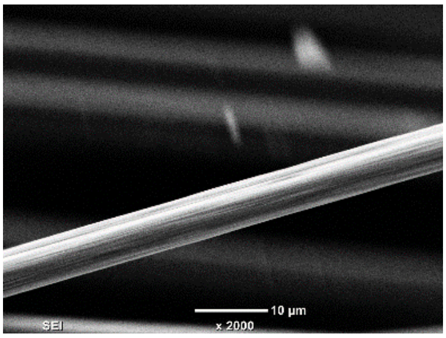
Analysis:
Pyrolysis is a mature thermal recycling technology capable of reclaiming high-quality fibres. Operating temperatures typically range from 500°C to 700°C, depending on the matrix composition and desired output. Cleaned fibres obtained through optimised pyrolysis retain up to 90% of their original mechanical properties, making them suitable for structural applications such as wind turbine blades and automotive components.

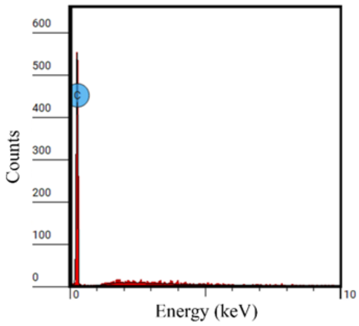
Additionally, pyrolysis generates by-products, including syngas and pyrolysis oil, that can be utilised for energy recovery, enhancing economic feasibility [119,120]. Despite these advantages, pyrolysis is energy-intensive and requires advanced operational controls to prevent fibre damage or resin residues. Its scalability and ability to process large volumes of waste, however, position it as a leading recycling technique, particularly for high-value CFRP composites.

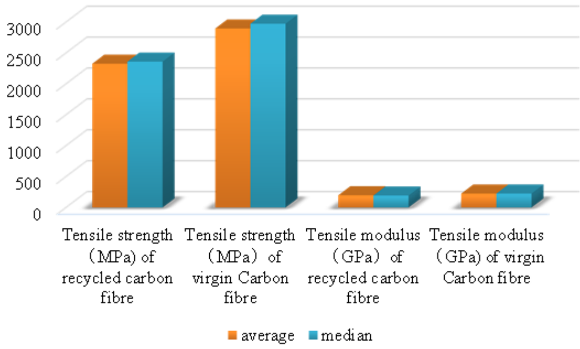
Case Study 4: Optimised Pyrolysis Process for Recycling of CFRP Composites

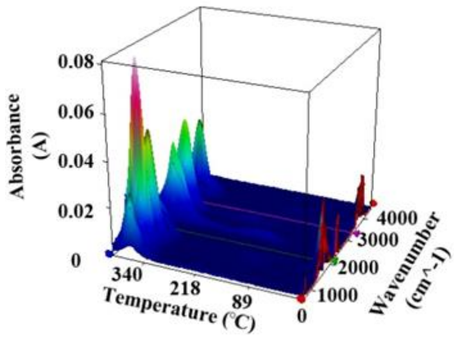
This case study demonstrates how to address two key challenges associated with thermal recycling approaches: elevated operational costs due to high energy consumption and the risk of fibre surface degradation from excessive heating. To overcome these challenges, researchers from the University of Sydney identified the optimal heating temperature and refined key operating parameters, including atmospheric conditions, heating rates, and isothermal dwelling time [111]. Achieving this requires a comprehensive understanding of the kinetic behaviour of CFRP thermal degradation, which enables the recovery of high-quality, undamaged fibres. Additionally, this analysis helps minimise energy consumption, improve byproduct control, and reduce CO2 and toxic gas emissions, thereby enhancing the environmental sustainability of the process.

The proposed optimisation led to significant improvements, with 87.6% retention of the fibre's tensile modulus and 80.3% of its strength following the recycling process. The approach was successfully applied to the recycling of bike forks, yielding promising results and confirming the method's potential for broader industrial application in FRP material recycling.









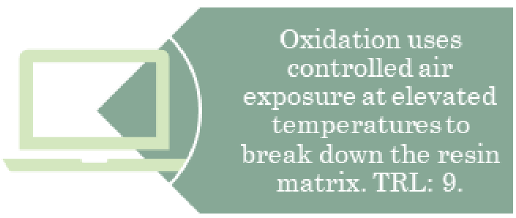
Case Study 5: FRP Wind Turbine Recycling in Australia

Australia's transition to a low-carbon energy future depends heavily on renewable sources, with wind power playing a pivotal role in reducing greenhouse gas emissions. Under the Climate Change Act 2022, the country has committed to a 43% reduction in emissions by 2030, making the expansion and sustainability of clean energy infrastructure a national priority. Wind energy, currently the second-largest contributor to Australia's clean energy mix (35.6% of total clean electrical energy)—trailing only the combined output of rooftop and large-scale solar—serves as a key driver in decarbonising the national electricity grid. However, alongside its expansion, the industry faces a critical challenge: the decommissioning of ageing wind farms.

As some of Australia's earliest wind farms near the end of their operational lifespan, decommissioning and waste management have become pressing concerns. A primary issue is the disposal of wind turbine blades, which are composed of composite materials that are difficult to recycle. According to a Clean Council report [121], within a decade, an estimated 15,000 tonnes of composite blade waste will be generated nationwide, with peak annual volumes reaching up to 4,000 tonnes in certain years.

This growing waste stream presents both an environmental challenge and an opportunity for innovation. Currently, mechanical grinding is the predominant recycling method for wind turbine blades, breaking them down into short fibres and ground composite material. This approach is widely used in Germany, where specialised companies manage fibreglass waste through a combination of mechanical processing, cement kiln co-processing, and logistical coordination for material transport to recycling facilities. Beyond mechanical processing, thermal recycling has gained traction in other regions. This method subjects composite materials to high temperatures, recovering clean fibres while harnessing the energy stored in the resin matrix.

Unlike some European counterparts, Australia lacks a mature infrastructure for large-scale wind turbine blade recycling. The industry remains in its early stages, with limited facilities capable of handling the anticipated waste volumes.



Oxidation

Summary and TRL:

Oxidation uses controlled air exposure at elevated temperatures to break down the resin matrix.
TRL: **9**.

Analysis:
Oxidation is a derivative of pyrolysis, operating at slightly lower temperatures (~600°C) due to the presence of oxygen. This facilitates faster resin degradation but poses risks of fibre oxidation, especially under prolonged exposure or poor temperature regulation. Recovered fibres are generally comparable in quality to those from pyrolysis, retaining their structural properties with minimal resin contamination [122].

Although oxidation is less energy-intensive, the presence of oxygen introduces challenges, such as increased risk of uncontrolled combustion. To mitigate this, advanced air-flow systems and precise temperature regulation are essential. Despite these challenges, oxidation is well-suited for industrial-scale adoption, particularly for waste streams with mixed thermoset matrices.

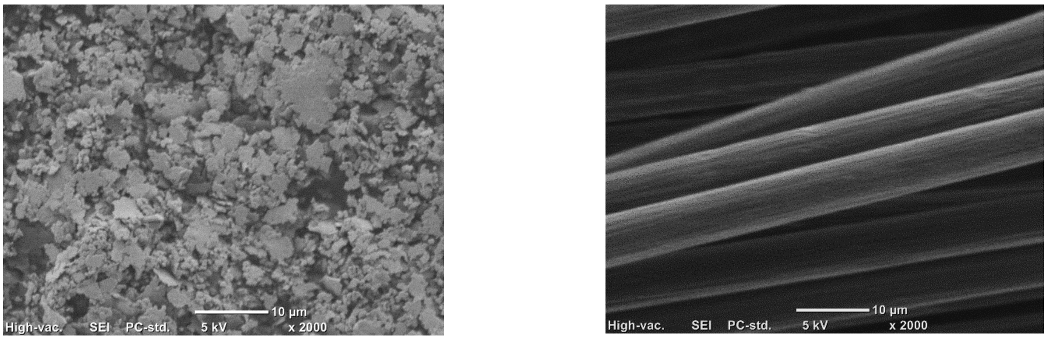
Case Study 6: Development of an Innovative CFRP Hybrid Recycling Method

Process Innovation and Mechanism

The innovative recycling method which was developed by researchers at the University of Sydney is based on a carefully optimised set of process parameters designed to maximise both material utilisation and energy efficiency. A key feature of this technique is its two-step process, beginning with solvolysis pre-treatment, followed by pyrolysis and oxidation with an optimized heating rate [123]. The solvolysis stage effectively prepares the CFRP for subsequent thermal processing by facilitating the breakdown of the composite at lower temperatures, thus reducing energy consumption.

Kinetic analysis has shown that the solvolysis pre-treatment introduces an additional preliminary reaction stage, which is absent in untreated CFRP. This early-stage breakdown not only lowers the temperature required for subsequent steps but also results in improved retention of the mechanical properties of the fibres.

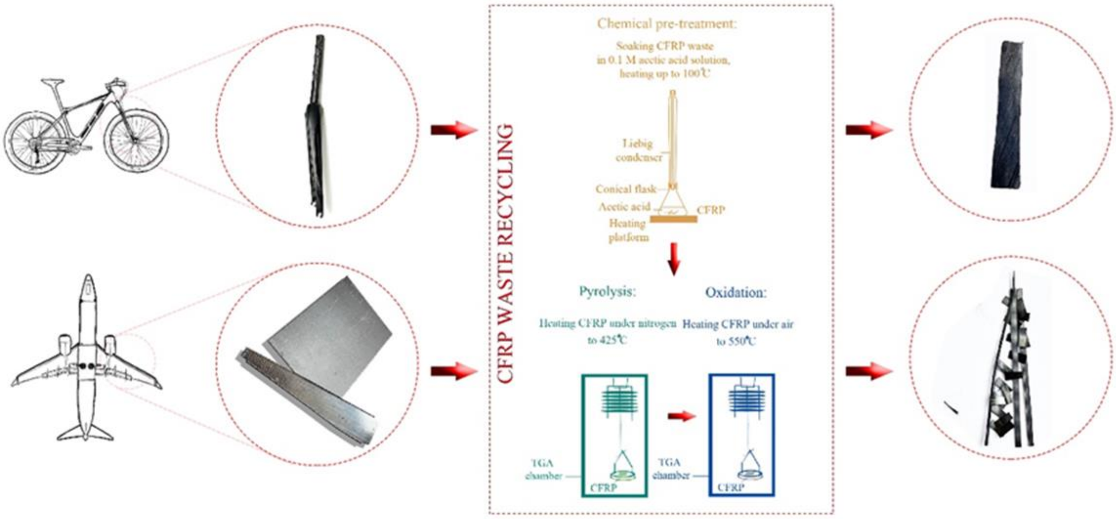
By minimising heat exposure during recycling, the process ensures that the strength of the recycled fibres remains as high as 92.9% of their virgin strength, a 10.21% improvement over fibres recovered via conventional thermal degradation alone. This high level of fibre preservation makes the hybrid thermo-chemical method a significant advancement over traditional recycling techniques, which often compromise fibre integrity due to excessive heat exposure.



SEM Images for CFRP after chemical pre-treatment and fibre recovered with optimised thermo-chemical recycling technique

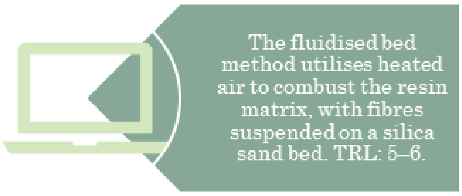
Evaluation through Practical Applications

The practical viability of the hybrid recycling method was assessed using real-world CFRP waste, including scraps from a bicycle fork and an aeroplane. These materials, made from high-strength unidirectional and bi-directional carbon fibre mats, provided a valuable opportunity to evaluate the efficiency of the technique under varying conditions. The bicycle fork, which was coated with a sealant, allowed the team to examine the impact of coating removal on recycling efficiency and fibre quality. The aeroplane scraps, composed of uncoated bi-directional mats, were used to explore potential challenges related to the different chemical compositions of the matrix. The results from recycling the bicycle and aircraft components indicated that process parameters need to be slightly adjusted depending on the CFRP type and matrix composition. Moreover, it was found that coatings must be thoroughly removed from the components prior to recycling to prevent significant fibre damage during the polishing process.



Fluidised Bed

Summary and TRL:
The fluidised bed method utilises heated air to combust the resin matrix, with fibres suspended on a silica sand bed.
TRL: **5–6**.



Analysis:
The fluidised bed method provides an efficient mechanism for thermal degradation, enabling energy recovery from polymer combustion [124]. However, the high temperatures (above 600°C) involved often result in a loss of fibre strength, with GFRP fibres retaining only about 67% of their original tensile properties. This limits the method's viability for high-performance structural applications, confining its outputs to lower-grade uses such as fillers or insulation materials.

A key advantage of the fluidised bed method is its adaptability to different scales of operation, making it attractive for smaller facilities [125]. Nevertheless, the inconsistent quality of the recovered fibres and significant capital costs for advanced thermal systems constrain its industrial applicability [126].

Solvolysis

Summary and TRL:
Solvolysis dissolves the resin matrix using solvents under controlled conditions, producing clean fibres with minimal surface damage.
TRL: **5–6**.

Analysis:

Solvolysis is a chemical recycling method that offers unique advantages, such as the ability to reclaim fibres with smooth surfaces and high tensile strength retention [127]. Recent advancements, including the use of eco-friendly solvents like n-propanol, have enhanced the process's environmental and operational efficiency. Despite its potential, solvolysis faces significant technical and economic challenges. The disposal of residual solvent and by-products poses environmental risks, while the method’s slow processing times and high operational costs hinder large-scale adoption. In laboratory settings, solvolysis has demonstrated excellent outcomes for CFRPs, making it a promising area for future research and development.

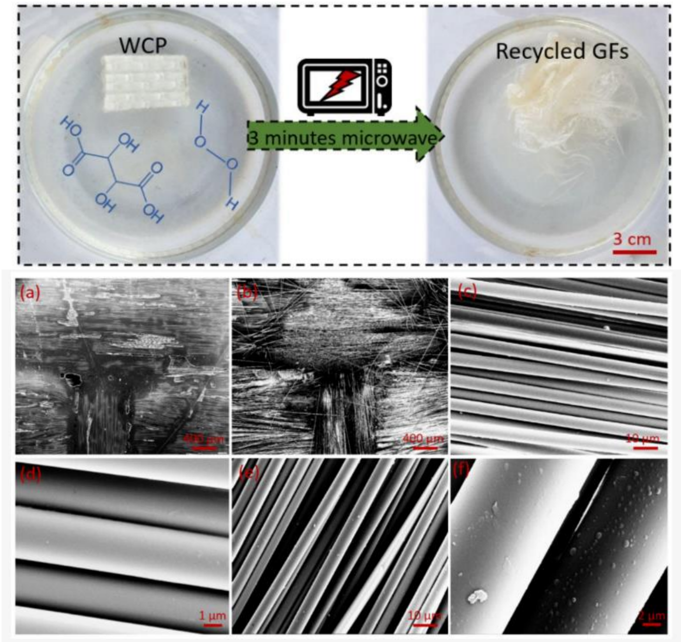
Case Study 7: Advancing Microwave-Assisted Chemical Recycling of FRP Wastes

Recent advancements in composite chemical recycling technologies, introduced by a research group from Deakin University, include a promising microwave-assisted chemical recycling method. This method operates in a green oxidative medium to efficiently reclaim carbon and glass fibres from waste composites. This method is applied in a very short period of time, allowing for the rapid and effective breakdown of the polymer matrix without the need for pyrolysis [128,129].

In the case of Carbon Fibre Reinforced Polymers (CFRP), this chemical recycling process utilizes microwave radiation to accelerate the oxidative degradation of the polymer matrix, enabling the recovery of high-quality carbon fibres. The reclaimed fibres maintain their mechanical integrity, making them suitable for reuse in manufacturing new composite materials. This method offers a significant reduction in energy consumption and environmental impact compared to traditional recycling techniques.

A similar approach has been successfully applied to glass fibre composites, where the microwave-assisted chemical recycling process allows for the recovery of glass fibres from the polymer matrix. The method ensures the fibres are reusable, contributing to a circular economy and reducing waste in industries that rely on composite materials.

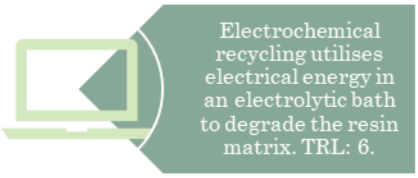
These innovative chemical recycling methods are key to promoting sustainability in the composite materials industry, offering efficient and eco-friendly solutions for the reclamation of valuable fibres from waste composites.



SEM images of the WCP (a) before and (b) after recycling process, and SEM images of (c,d) VGFs and (e,f) reclaimed RGFs5

Electrochemical Recycling

Summary and TRL:
Electrochemical recycling utilises electrical energy in an electrolytic bath to degrade the resin matrix.
TRL: **6**.



Analysis:
Electrochemical recycling is a low-energy, environmentally friendly alternative to thermal and chemical methods. Operating at room temperature, this technique uses an electrolytic solution to gradually break down the matrix, allowing fibres to be reclaimed with minimal surface contamination [130]. The reusability of the electrolyte medium contributes to its cost-effectiveness.

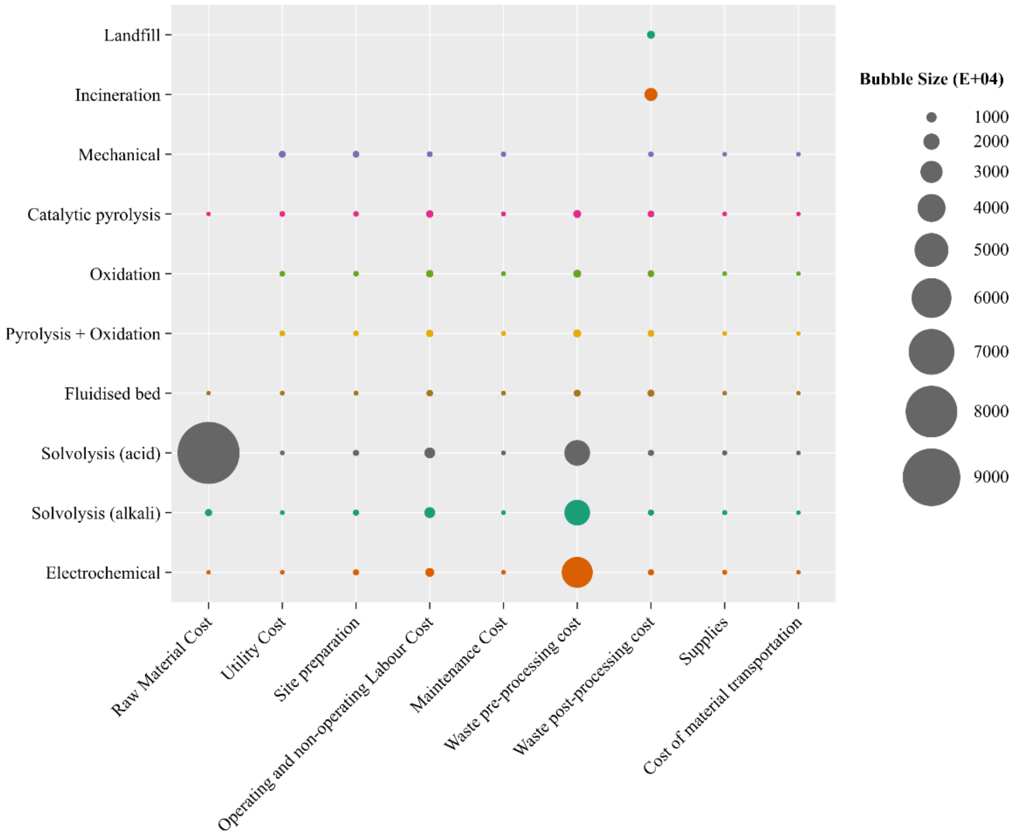
However, the process is time-intensive, with each recycling cycle lasting up to 24 days, including necessary drying periods. The scalability of electrochemical methods remains a challenge, particularly for industries requiring rapid processing of large waste volumes. Nonetheless, the method's simplicity and low operational costs make it a viable option for niche applications or as a complementary process.

Economic Feasibility of CFRP and GFRP Recycling: Cost-Benefit Analysis

The economic behaviour of different FRP waste treatment methods has been assessed through a cost-benefit analysis. The cost analysis considers both capital investment and ongoing operational costs, with the sub-cost divisions shown in the following figure.

The capital investment required for various FRP waste treatment methods reveals key trends that influence the economic feasibility of each technique. Factory setup costs dominate the initial investments, especially for electrochemical and thermal recycling methods, where establishing a production facility is the primary expense. This reflects the need for specialised infrastructure and equipment capable of handling complex FRP materials and processing them at scale. Chemical recycling methods, such as solvolysis, require higher capital investment due to the purchase of raw materials, particularly acids and solvents. This is particularly evident in acid-based solvolysis, where stronger chemicals, such as tartaric acid and hydrogen peroxide (H_2O_2), are necessary to dissolve the matrix of carbon fibre and glass fibre composites.

When examining the operational costs, a trend emerges across different FRP recycling methods, reflecting varying levels of complexity and energy consumption. Solvolysis and electrochemical techniques, which rely on energy-intensive processes and expensive reagents, incur higher ongoing costs compared to mechanical recycling. Although electrochemical recycling operates at room temperature and is promising in terms of energy efficiency, the high cost of long-term electrical supply poses a significant barrier to its widespread industrial adoption. Thermal recycling methods, including pyrolysis and catalytic pyrolysis, tend to offer a more balanced approach between capital investment and operational expenditure. These techniques, which rely on heat to break down the polymer matrix, benefit from more established technologies and, in some cases, the ability to recover energy during the process. This characteristic significantly reduces operational costs, making these methods more economically attractive in the long term.



CFRP Cost Breakdown for Various FRP Waste Management Approaches

Trends in Market Demand and Fibre Quality

The quality of recycled fibres plays a pivotal role in determining the economic viability of different recycling methods. Fibres with higher tensile strength and modulus of elasticity are more valuable and have a broader range of potential applications in the manufacturing of new products. Chemical and thermal recycling methods, which have the potential to preserve the mechanical properties of the fibres, open up markets for high-value products. In contrast, mechanical recycling often results in fibres of lower quality, primarily due to the physical damage sustained during the grinding or shredding process. As a result, mechanically recycled fibres are typically used in non-structural applications or fillers.

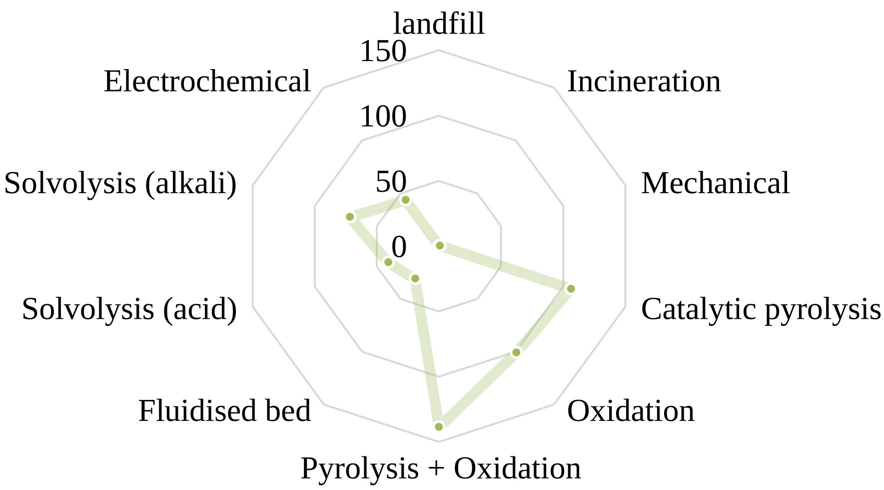
Furthermore, the market demand for recycled fibres is strongly influenced by the specific needs of different industries. For instance, the demand for high-quality recycled carbon fibre (CF) is growing, particularly in sectors such as automotive and wind energy, where performance is critical. On the other hand, glass fibres, although widely used, are often less valuable when recycled due to their lower mechanical performance and the difficulty in preserving fibre integrity through recycling processes. This trend further compounds the economic challenges associated with GFRP recycling, as the cost of recovery often outweighs the economic return.

Economic Efficiency and Regional Variability

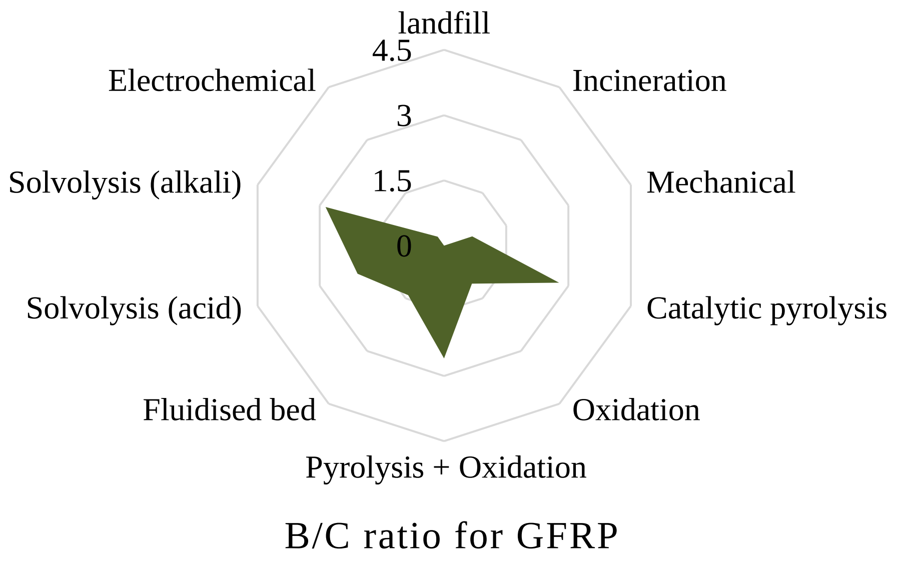
The Cost-Benefit Analysis (CBA) indicates that the solvolysis method offers the highest profit potential for fibre recovery from FRP waste, primarily due to its substantial net profit value [110]. However, the performance of solvolysis can vary depending on the chemical solution used. Solvolysis with an acid solution requires a higher capital investment and results in lower-quality recycled fibres following acidification, compared with alkali-based solvolysis.

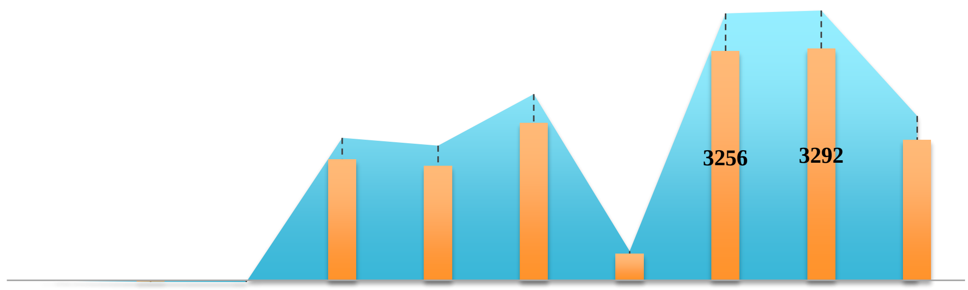
Thermal recycling methods, such as catalytic pyrolysis and pyrolysis combined with oxidation, also provide good economic returns and exhibit a higher Benefit-Cost Ratio (B/C ratio) due to their efficient energy use and ability to recover valuable materials. The B/C ratio, an indicator of the relationship between costs and expected benefits of a specific waste treatment pathway, is calculated by dividing net income (total benefits minus corporate income tax) by the sum of capital and operational costs.

The B/C ratios for different methods are shown in the following figure. Regional differences further influence the economic returns of these recycling methods. In regions like Europe, where renewable energy sources are well-established, thermal recycling methods benefit from lower operational costs and greater energy efficiency, along with favourable regulatory environments and governmental incentives for sustainable waste management. In contrast, mechanical recycling is currently more economically attractive in Australia, owing to lower energy costs and simpler technology. However, the profitability of mechanical recycling remains limited by the low value of the recycled fibres, which restricts its potential for growth.



B/C ratio for CFRP





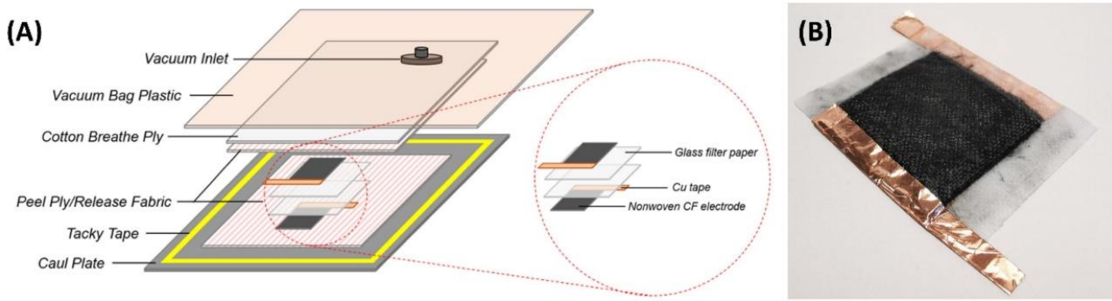
	landfill	Incineration	Mechanical	Catalytic pyrolysis	Oxidation	Pyrolysis + Oxidation	Fluidised bed	Solvolysis (acid)	Solvolysis (alkali)	Electrochem ical
Europe	-9	-21	-25	2025	1915	2648	416	3796	3836	2336
Australia	-5	-11	-4	1716	1624	2240	375	3256	3292	1997

Figure 1Net Profit Comparison Between European and Australian Markets

Case Study 8: Application of Recycled Products: The use of recycled carbon fibre as capacitor electrodes

Recycled carbon fibres are typically shorter than virgin carbon fibres, which may limit their use in some primary structural reinforcement applications. However, the potential of recycled carbon fibres extends beyond merely reusing them for the same purposes as before. Researchers are continually developing various applications for the incorporation of recycled carbon fibres as a substitute for virgin fibre.

Researchers at Deakin University have pioneered high-value applications for reclaimed fibres, particularly through a surface modification approach that endows them with energy storage capacities, enabling their use as load-bearing supercapacitors [131]. In this work, carded non-woven reclaimed carbon fibre fabrics were modified with a conductive polymer coating to provide faradaic capacitance. This modification also improved the interfacial adhesion in the final composite due to the covalent binding of the conductive polymer to the fibre surface. These findings further underscore the high potential value of reclaimed carbon fibres as a raw material source through innovative applications.



(A) The assembly of the laminate devices and (B) a finished device produced using the method described

Application of recycled product --- Enhancing Structural Applications with Recycled Fibre in Concrete: Key Benefits and Innovations

The construction industry is undergoing a significant transformation, driven by the need to reduce environmental impact and promote sustainability. One of the most promising innovations in this space is the use of recycled fibres in concrete. These fibres, derived from composite materials such as carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP), have considerable potential to enhance the performance and durability of concrete structures, while contributing to a circular economy by diverting waste materials from landfills. The benefits of incorporating recycled fibres into concrete, focusing on improvements in mechanical properties, durability, and environmental sustainability, as well as the associated cost advantages will be shown here. A detailed case study is provided, demonstrating the use of recycled carbon fibres (CFs) derived from lab-used composite offcuts and mechanically recycled CFRP (rCFRP) powder sourced from industrial aerospace panels in cement-based mortars [40].

The Role of Recycled Fibre in Concrete:

Concrete is widely used for its versatility and affordability, but its performance is often limited by weaknesses in tensile strength, crack resistance, and overall durability. These limitations are particularly pronounced in structures exposed to aggressive environmental conditions or subjected to heavy traffic loads. The inclusion of fibres in concrete is a proven method to address these issues, enhancing the material's structural integrity and overall performance. Recycled fibres, especially those derived from waste CFRP and GFRP composites, offer a sustainable alternative to traditional reinforcements such as steel. The use of recycled fibres not only improves the physical properties of concrete but also reduces reliance on virgin materials, making it a vital component of sustainable construction practices. Incorporating recycled fibres into concrete leads to significant enhancements in multiple performance aspects.

Researchers at the University of Sydney have shown that concrete reinforced with recycled fibres demonstrates an increase in tensile strength of approximately 15-20% compared to unreinforced concrete. This enhancement in tensile strength is crucial for preventing cracking under stress, thus ensuring the structural integrity of concrete elements. Additionally, recycled fibres have been shown to increase the compressive strength of concrete by 10-15%, further improving its load-bearing capacity. These gains in mechanical performance make recycled fibre-reinforced concrete an ideal solution for high-performance applications such as bridges and other infrastructure elements.

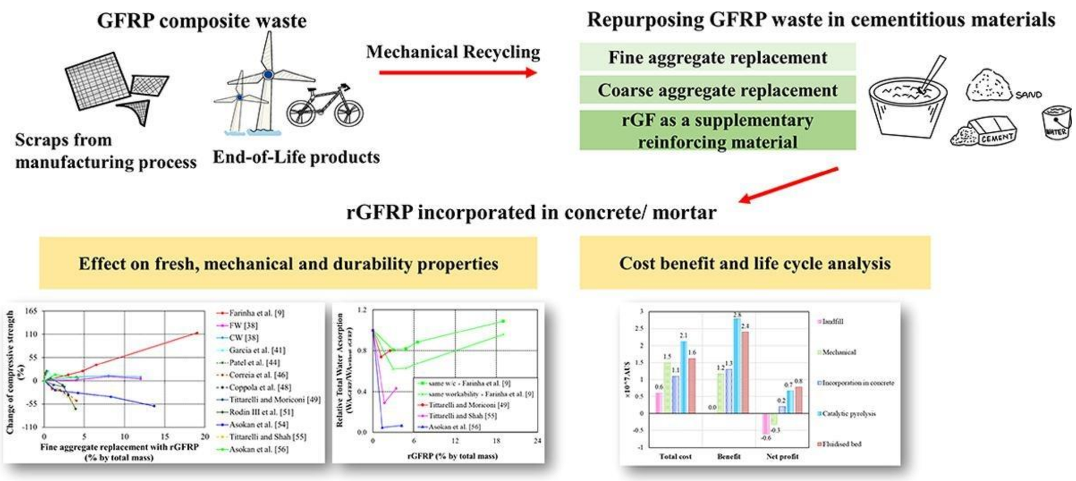
Another critical advantage is the improvement in durability and resistance to environmental degradation. These fibres help create structures that require less maintenance over their service life. Concrete structures are often exposed to harsh environmental conditions, including freeze-thaw cycles, chemical exposure, and high moisture levels, all of which contribute to deterioration over time. Recycled fibres, particularly those derived from CFRP, offer excellent resistance to corrosion, outperforming traditional steel reinforcements in this regard.

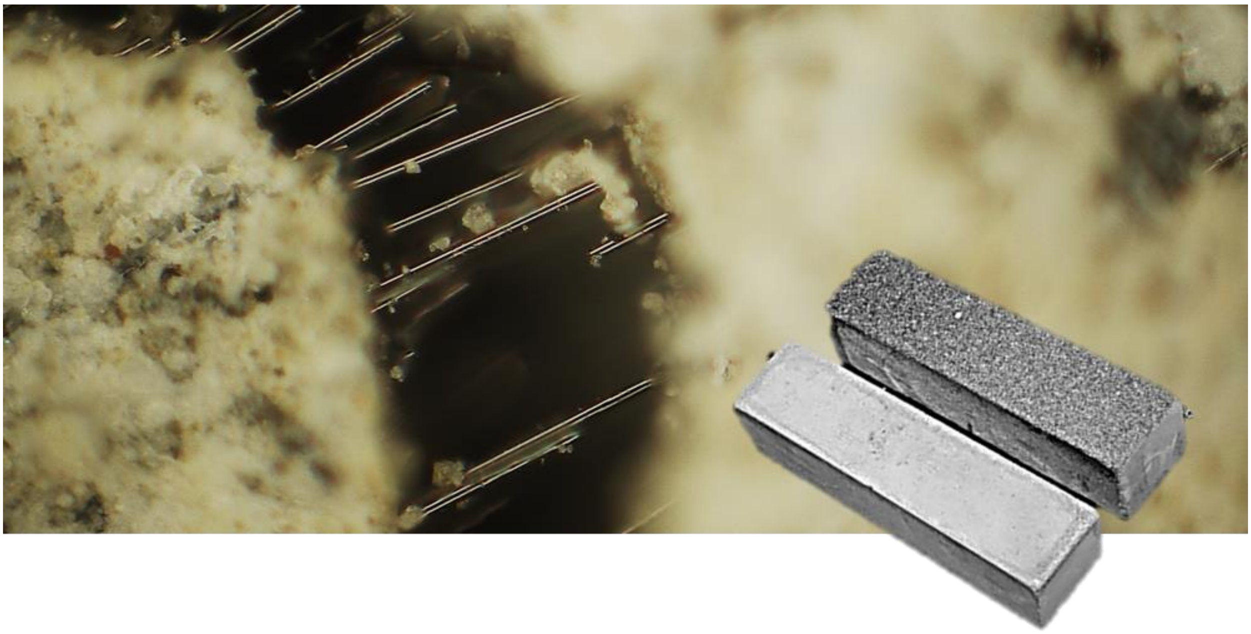
Studies have demonstrated that recycled fibre-reinforced concrete exhibits 20-30% greater corrosion resistance compared to conventional steel-reinforced concrete, which significantly extends the lifespan of structures exposed to corrosive environments such as marine or de-icing applications. Furthermore, the fatigue resistance of concrete is greatly enhanced by the inclusion of recycled fibres. Concrete reinforced with recycled fibres has shown a 25-30% increase in service life under repetitive loading conditions, such as those experienced by roadways and bridges. This is a crucial benefit, as it leads to fewer repairs and lower long-term maintenance costs, reducing the overall lifecycle costs of concrete structures and decreasing the accumulated waste.

In addition to their mechanical and durability improvements, recycled fibres contribute significantly to environmental sustainability. Concrete production, particularly the manufacturing of cement, is responsible for a substantial portion of global CO_2 emissions. The production of recycled fibres requires up to 60% less energy compared to the manufacture of virgin fibres, making it a more environmentally friendly alternative.

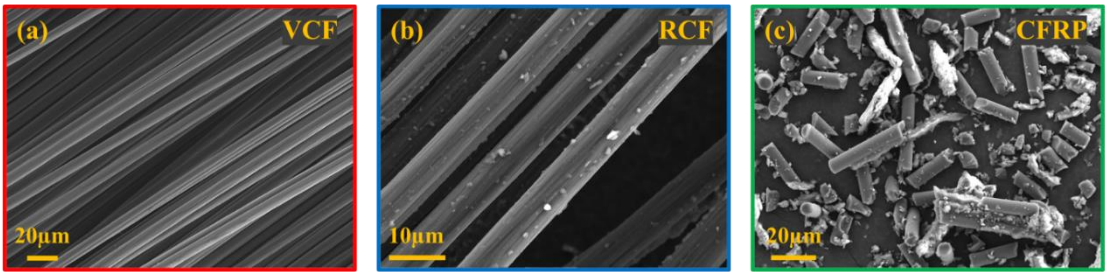
Furthermore, the use of recycled fibres in concrete aids in waste minimisation by diverting composite materials such as CFRP and GFRP from landfills. Life cycle assessments of concrete containing recycled fibres have shown a 25% reduction in CO2 emissions compared to concrete with traditional steel reinforcements, due to the energy savings in the recycling process and the lower carbon footprint associated with the production of recycled fibres. This reduction in emissions aligns with broader sustainability goals, positioning recycled fibre-reinforced concrete as a key solution for low-carbon construction.

Finally, the economic benefits of using recycled fibres in concrete are compelling. Recycled fibres are typically around 1/3 less expensive than virgin materials, such as steel or high-performance synthetic fibres, making them a cost-effective choice for reinforcing concrete. In addition to direct material savings, the durability improvements offered by recycled fibres can lead to significant cost reductions over the service life of concrete structures. Concrete reinforced with recycled fibres exhibits lower maintenance costs, with studies indicating over 20% reduction in lifecycle costs compared to traditional concrete.





Case Study 9: the use of recycled aerospace panels in cementitious composites



The carbon-based fillers used in the mix

The research carried out by researchers in the School of Civil Engineering at the University of Sydney, highlights the benefits of using recycled carbon fibres (rCF) in concrete. This demonstrates several advantages:

- **Enhanced Mechanical Properties:** The incorporation of recycled carbon fibres (rCF) and recycled carbon fibre-reinforced polymer (rCFRP) significantly improves the compressive strength of cementitious composites. Specifically, the inclusion of rCFRP led to a remarkable 67% increase in compressive strength at the optimal dosage, surpassing the performance of virgin carbon fibres (vCF) in this regard.
- **Improved Workability:** While the addition of virgin carbon fibres (CFs) resulted in reduced flowability and increased fresh density due to fibre aggregation, the integration of rCFRP enhanced flowability by optimising particle packing and reducing inter-particle friction. This improvement facilitates easier handling during mixing and casting, and the resulting lower fresh density makes rCFRP composites a viable option for large-scale construction without sacrificing material strength.

- **Superior Electrical and Piezoresistive Performance:** Cementitious composites containing rCFRP demonstrated high sensitivity to temperature fluctuations, indicating their suitability for real-time structural health monitoring. Specifically, rCFRP composites exhibited a stress sensitivity of 0.42%/MPa and a high gauge factor of 1749.56 in a 30% humidity environment. This stable piezoresistive behaviour remained consistent even after exposure to chloride corrosion, underscoring the potential for rCFRP composites to maintain performance over extended periods and under diverse environmental conditions. In contrast, composites with higher CF dosages showed limited sensitivity to humidity changes and exhibited less dynamic conductivity, which would undermine their suitability for real-time sensing applications.
- **Sustainability:** The use of recycled carbon fibres (rCF) and rCFRP in cementitious composites offers a sustainable solution by repurposing waste materials, thus reducing the environmental impact associated with both fibre disposal and raw material extraction.

Appendices

Sustainable Waste Management in the Composite Industry

Designed by:
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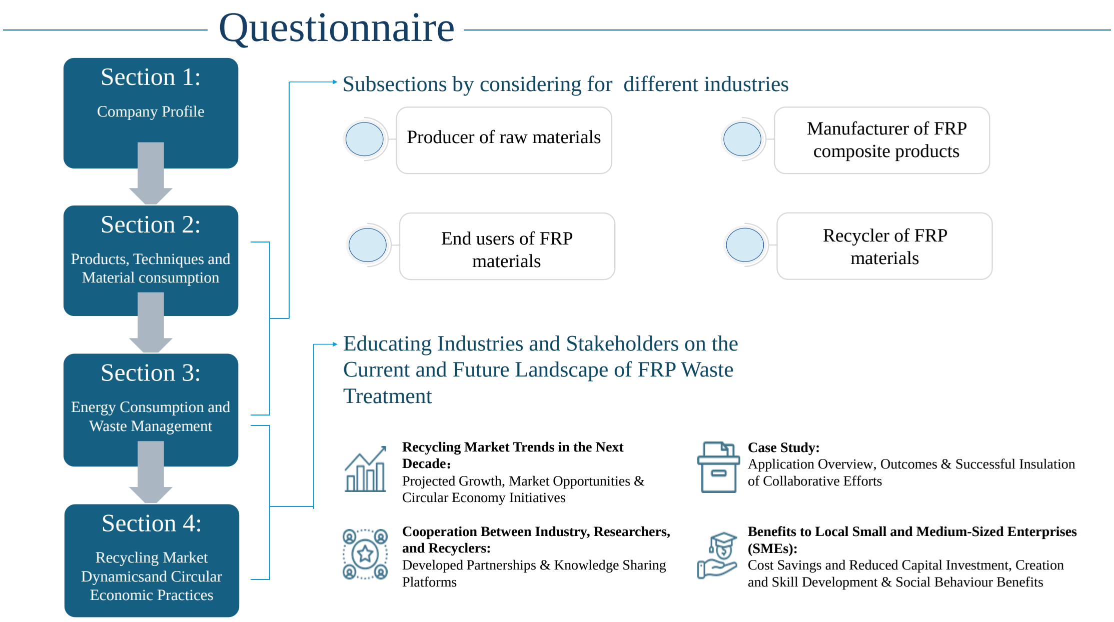
Address: Civil Engineering Building J05, The University of Sydney, 2006

Purpose of the Questionnaire:

Thank you for taking the time to complete this questionnaire. This study will support the ACM CRC PROJECT HPN002: Sustainable Waste Management Scoping Study. This questionnaire focuses on FRP marketing, FRP recycling practices, waste treatment processes, and other aspects related to FRP waste management. This aims to collect comprehensive data on the current state of FRP composite recycling. The questions are designed to enhance our understanding of global and Australian best practices, waste production, usage and recycling rates, end-of-life technologies, waste management strategies, and to develop actionable recommendations. The objective is to evaluate how recycled fibre processes are integrated into industrial operations and to identify best practices that could improve sustainability and efficiency within the industry. This study informs the production of the white paper at the end of the project which we expect to be published in December 2024. The white paper will serve as a valuable resource for industry stakeholders, government agencies, and academia, facilitating the transition towards a circular economy in Australia.

Your participation in this survey is entirely voluntary and greatly appreciated. The questionnaire is expected to take approximately 7 minutes to complete. Your insights are crucial to the success of this research.

No sensitive commercial details will be included in the study's findings. However, with your additional agreement and confirmation, your company's response may be included as a case study in the white paper. The section related to your company will be sent to you for review before disclosure, and it will not be published without your approval.



Google form:

https://docs.google.com/forms/d/e/1FAIpQLSeVWTjge9d3JtqFr2_gOIDKzP5R_8CWEnGtmgWVHET79mUktg/viewform?usp=sf_link

More information:

Section 1: Company Profile

The following questions pertain to basic information about your company.

1.1 Name of your company:

____

1.2 Basic contact information you wish to include for promoting your company in the white paper:

Contact Person: ____

Email:____

Phone:____

1.3 Number of employees:

- ○ Less than 10

- 10-50
- 50-200
- 200-1,000
- More than 1,000

1.4 Do you export your products to other countries?

- Yes, please indicate the countries in below
- No

1.5 Please indicate the primary role of your company in the FRP industry:

- Producer of raw materials (e.g. fibre, resin, tooling products etc) → Go to Section 2A
- Manufacturer of FRP composite products (FRP composite com[ponents etc) → Go to Section 2B
- End user of FRP composite products → Go to Section 2C
- Recycler of FRP materials → Go to Section 2D

Section 2:

Section 2A: For Producer of raw materials: Products, Techniques and Material consumption for Raw Material Producers

2.1 What is the main source of materials you use in your production?

- Virgin materials
- Recycled materials
- Blended (mix of virgin and recycled materials)

2.2 What percentage of your raw material production consists of recycled or secondary materials?

- 0%
- 1–10%
- 11–25%
- 26–50%
- 51–75%
- More than 75%

2.3 Do you have any waste recovery or recycling processes in place during raw material production?

○ Yes, please describe the process

○ No → Go to Question 2.5

2.4 Do you use your recycled materials directly in your production, or do you sell them to other industries for repurposing?

○ Use directly in our own production

○ Sell to other industries for repurposing

○ Both (use internally and sell externally)

○ Other, please specific in below

2.5 Please rank the factors that influence your choice of production techniques from 1 (most influential) to 6 (least influential):

□ Cost-effectiveness

□ Production efficiency

□ Production quality

□ Environmental impact

□ Technological advancements for easy operations

□ Other, please specific in below

2.6 What are the primary challenges in implementing sustainable practices in raw material production? Please rank the following from 1 (most challenging) to 6 (least challenging).

□ High implementation costs

□ Limited access to sustainable materials

□ Regulatory compliance and complexity

□ Lack of customer demand for sustainable products

□ Technological limitations or barriers and insufficient expertise or knowledge

□ Other, please specific in below

→ Go to Section 3A

Section 2B: For Manufacturer of FRP composite products: Products, Techniques and Material consumption for FRP Producers

2.1 Would you please provide the total volume or weight of products imported or purchased over the course of the 2024 financial year?

	Type	Volume/Weight
○	Glass fibre	【 】
○	Carbon fibre	【 】
○	Other fibres	【 】
○	Resin systems	【 】
○	Inert fillers	【 】
○	Release agent	【 】
○	Vacuum bags	【 】
○	Brushes and other ancillary products	【 】
○	Other (please specify in below)	【 】

2.2 What is the main source of materials you use in your production?

- ○ Virgin materials → Go to Question 2.4
- ○ Recycled materials
- ○ Blended (mix of virgin and recycled materials)

2.3 What percentage of your raw material production consists of recycled or secondary materials?

- ○ 0%
- ○ 1–10%
- ○ 11–25%
- ○ 26–50%
- ○ 51–75%

○ More than 75%

2.4 Do you have any waste recovery or recycling processes in place during FRP production?

○ Yes, please describe the process

○ No → Go to Question 2.6

2.5 Do you use your recycled materials directly in your production, or do you sell them to other industries for repurposing?

○ Use directly in our own production

○ Sell to other industries for repurposing

○ Both (use internally and sell externally)

○ Other, please specific in below

2.6 Which sector do your FRP products primarily serve? (Multiple choices available.)

	Type	More information	
○	Construction	A percentage of total annual sales attributed to this product category out of all products.	_______________ %
○	Automotive	A percentage of total annual sales attributed to this product category out of all products.	_______________ %
○	Aerospace	A percentage of total annual sales attributed to this product category out of all products.	_______________ %
○	Renewable energy	A percentage of total annual sales attributed to this product category out of all products.	_______________ %
○	Sports goods	A percentage of total annual sales attributed to this product category out of all products.	_______________ %

○	Marine infrastructure	A percentage of total annual sales attributed to this product category out of all products.	______________ %
○	Other (please specify): _____________________ _________________	A percentage of total annual sales attributed to this product category out of all products.	______________ %

2.7 What significant trends are influencing the FRP market within your primary end-user industries? (Multiple choices available.)

- ○ Increased Demand for Lightweight Materials
- ○ Growing Focus on Sustainability
- ○ Advances in Composite Technologies
- ○ Regulatory Changes
- ○ Changes in Consumer Preferences
- ○ Corrosion Resistance
- ○ Cost Efficiency
- ○ Durability and Longevity
- ○ Design Flexibility
- ○ Compliance with Environmental Regulations
- ○ Other, please specify in below

2.8 What challenges or barriers does your company face in the FRP market for each end-user industry?

- ○ Regulatory Compliance
- ○ Technological Constraints
- ○ Market Competition
- ○ Cost of Raw Materials
- ○ Customer Awareness
- ○ Other (please specify in below):

○ No significant challenges

→ Go to Section 3A

Section 2C: For End user of FRP composite products: Applications of FRP for End Users

2.1 What is your industry sector?

- ○ Construction
- ○ Automotive
- ○ Aerospace
- ○ Renewable energy
- ○ Sports goods
- ○ Marine infrastructure
- ○ Other (please specify in below):

2.2 How do you source your FRP materials?

- ○ Purchased raw materials and manufacture them by yourself
- ○ Purchased regular products from FRP suppliers and adjust/assemble the loose FRP components by yourself
- ○ Purchased customised FRP product which can be directly used or install on your final products
- ○ Other (please specify in below):

2.3 How many tonnes of FRP products did you purchase during the financial year of 2024?

_________________tonnes

2.4 What factors influence your choice of FRP suppliers?

- ○ Cost effective
- ○ Product Quality
- ○ Delivery
- ○ Sustainability

- ○ Customer support
- ○ Supplier reputation
- ○ Other (please specify in below):

2.5 What challenges do you face when using FRP materials?

- ○ High material costs
- ○ Hard to reshape or install it
- ○ Technical expertise requirements
- ○ Low yield rates in production, i.e. High levels of waste generated during processing
- ○ Difficulty in recycling FRP materials & Issues with reusability of FRP products
- ○ Transportation challenges
- ○ Other (please specify in below):

2.6 Are you planning to increase your use of FRP materials in the future?

- ○ Yes
- ○ No
- ○ Maybe

2.7 What types of FRP and recycled FRP (rFRP) do you currently use in your industry, and what do you plan to use in the future? Please select all that apply and provide the estimated tonnage or volume consumed during the financial year 2024 and projections for 2030.

	Type	Volume/Weight in 2024	Volume/Weight in 2030
○	CFRP		
○	GFRP		
○	Other FRP, (please specify in below)		
○	rCFRP		
○	rGFRP		

- ○ Other rFRP, (please specify in below)

[ ]

→ Go to Section 3B

Section 2D: Recycler of FRP materials: Techniques used by the Recyclers

2.1 How is your company involved in FRP recycling as a recycler?

- ○ Recycle in-house (internal recycling of FRP waste)
- ○ Collaborate with external FRP recycling companies, such as do the primary recycling/pre-treatments and then supply treated FRP waste to third-party recyclers
- ○ Other (please specify in below):

[ ]

2.2 What recycling methods have you applied in your industry?

- ○ Mechanical recycling
- ○ Thermal recycling
- ○ Chemical recycling
- ○ Hybrid recycling, such as thermo-chemical recycling, (please specify in below):

[ ]

- ○ Other (please specify in below):

[ ]

2.3 What types of FRP waste does your company recycle?

- ○ CFRP
- ○ GFRP
- ○ Other, please specific in below

[ ]

2.4 What is the source of the FRP waste you recycle? Also, please give the annual volume/weight you recycled in the financial year of 2024.

Type **Volume/Weight**

- ○ Manufacturing wastes from FRP manufacturers 【 】
- ○ End-of-life FRP products (e.g., wind turbines, vehicles) 【 】
- ○ Offcuts from FRP end users 【 】
- ○ FRP waste supplied directly by government agencies or partner companies 【 】
- ○ FRP waste from unknown or mixed sources 【 】
- ○ Other (please specify in below) 【 】

[ ]

2.5 How much FRP waste did your company receive from each of the following sectors?

	Type	More information	
○	Construction	A percentage of this category out of all wastes.	______________ %
		Total volume/weight during the financial year 2024	________________
○	Automotive	A percentage of this category out of all wastes.	______________ %
		Total volume/weight during the financial year 2024	________________
○	Aerospace	A percentage of this category out of all wastes.	______________ %
		Total volume/weight during the financial year 2024	________________
○	Renewable energy	A percentage of this category out of all wastes.	______________ %
		Total volume/weight during the financial year 2024	________________
○	Sports goods	A percentage of this category out of all wastes.	______________ %
		Total volume/weight during the financial year 2024	________________

- ○ Marine infrastructure — A percentage of this category out of all wastes. ______________ %

  Total volume/weight during the financial year 2024 ________________

- ○ Other (please specify): ______________________ __________________ — A percentage of this category out of all wastes. ______________ %

  Total volume/weight during the financial year 2024 ________________

2.6 What are the main challenges in sourcing FRP waste?

- ○ Inconsistent supply of waste
- ○ High transportation costs
- ○ Contamination or coating of FRP materials
- ○ Other (please specify in below):

2.7 What are the main challenges your company faces in recycling FRP materials?

- ○ High costs
- ○ Technical difficulties
- ○ Lack of market demand
- ○ Regulatory barriers
- ○ Other (please specify in below):

2.8 How much did you invest in recycling FRP?

Capital investment:	
Annual operational investment:	
Pay to collaborated external FRP recycling companies (if applicable):	

2.9 What advancements or improvements have you made or are you interested in your recycling processes?

- ○ Improved fibre recovery rates
- ○ Improved recycled fibre recovery quality
- ○ Resin recovery
- ○ Cost effectively
- ○ Environmental friendly
- ○ Other (please specify in below):

2.10 What percentage of the original FRP material is typically recovered in your recycling process?

- ○ Less than 10%
- ○ 10%-20%
- ○ 20%-50%
- ○ 50%-80%
- ○ Over 80%

2.11 What percentage of the mechanical properties (e.g., strength, stiffness) of the fibres is retained after the recycling process?

- ○ Less than 50%
- ○ 50%-70%
- ○ 70%-80%
- ○ 80%-90%
- ○ Over 90%

2.12 How many tonnes of recycled fibres/resin did you produce in the financial year of 2024?

————————————————————————————————————

→ Go to Section 3C

Section 3:

Section 3A: For Producers: Material Efficiency, Energy Consumption and Waste Management during Production

3.1 Which of the following strategies have you implemented to enhance material efficiency in your production? If applicable, please provide further details on the process in the text box below.

- ○ Optimisation of material input and usage
- ○ Material substitution with lower-impact alternatives
- ○ Process automation to utilise waste generated during production (cycle system)
- ○ Other, please specific in below
- ○ No material efficiency strategies implemented

3.2 What is the average energy consumption of producing 1 tonne of each type of your product?

____
____
____
____

3.3 Please rank the sustainability measures your company would like to undertake in your production to reduce energy consumption (1 being most preferred and 5 being least preferred). If you have already applied any of these measures, please tick the box instead of ranking.

- ☐ Energy Efficiency Improvements via upgrade equipment or techniques
- ☐ Renewable Energy Sources, such as solar or wind Power
- ☐ Process Optimisation with capturing and reusing waste heat generated during production processes for heating or other energy needs
- ☐ Streamline supply chain logistics to reduce energy consumption in transportation and distribution
- ☐ Apply the statics analysis to seek the improvement, such as conducting LCAs to identify energy hotspots in production and seek improvements.
- ☐ Other, please specific in below

3.4 Approximately how much waste is generated per unit during production?

- ○ Less than 1%
- ○ 1–5%
- ○ 6–10%
- ○ 11–20%
- ○ More than 20%

3.5 How many tonnes of all your products were generated during the production phase in the financial year of 2020, 2021, 2023 and 2024?

____
____

3.6 Would you please list the types of waste generated during normal operations (not limited to the production phase) for the financial year 2024?

	Type	More information	
○	Off-cuts and Trimmings	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Defective Products	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Resin	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Other Chemicals (such as cleaning chemicals, equipment maintenance chemicals, catalyst and etc.)	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Release Agent	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Moulds	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________
○	Packaging and Containers	Weight of waste (for 2024) and related cost	_____________ tonnes

			AUD ________________
O	Other (please specify): ____________________	Weight of waste (for 2024) and related cost	_____________ tonnes AUD ________________

3.7 How is waste currently managed?

- O Recycled internally
- O Sent to external recyclers
- O Landfilled
- O Incinerated
- O Other, please specific in below

[ ]

3.8 What percentage of your total production cost is allocated to waste management?

- O Less than 1%
- O 1–5%
- O 6–10%
- O 11–20%
- O More than 20%

3.9 Has your company implemented any strategies to reduce waste during production?

- O Yes
- O No → Go to Question 3.11

3.10 How has your company worked to reduce waste during production? Please include any associated costs.

____

____

____________________________________3.11 Does your company track the waste generated when FRP products reach the end of their service life?

- O Yes, please specify in below

[ ]

- O No

Section 3B: For end users: Waste Management for the End Users of FRP Products

3.1 What types of FRP waste does your company generate?

- ○ CFRP,___________ tonnes in 2024
- ○ GFRP,___________ tonnes in 2024
- ○ Other, please specific in below

3.2 What is the source of the FRP related waste you generated? Also, please give the annual volume/weight you generated in the financial year of 2024.

	Type	**Volume/Weight**
○	Offcuts and scraps from FRP processing	【 】
○	Damaged or defective FRP products	【 】
○	End-of-life	【 】
○	Other (please specify in below)	【 】

3.3 How is the end-of-life waste from your FRP products typically managed? (Multiple choices available.)

- ○ Recycled
- ○ Repurposed for other applications
- ○ Landfilled
- ○ Incinerated
- ○ Other, please specific in below

3.4 How much did you spend on waste treatment?

AUD ____________________________

3.5 What percentage of your end-of-life products are currently being recycled?

- ○ Less than 10%
- ○ 10–25%
- ○ 26–50%
- ○ 51–75%
- ○ More than 75%
- ○ Not sure

3.6 What are your company's future plans for improving FRP waste management?

- ○ Implementing in-house recycling technologies
- ○ Collaborating with external recyclers
- ○ Developing waste storage and transportation system
- ○ Other, please specific in below

[ ]

3.7 How frequently do you audit or assess your company's waste management practices?

- ○ Annually
- ○ Every 2-5 years
- ○ More than five years
- ○ No regular audits, please specific in below

[ ]

3.8 What are your biggest concerns about the future of FRP waste management in your industry?

- ○ Financial incentives or government's grants/support
- ○ Environmental impacts of FRP disposal
- ○ Market demand for recycling/sustainable practices
- ○ Increasing regulatory pressure
- ○ Other, please specific in below

[ ]

Section 3C: For recyclers: Energy Consumption and Waste Management for FRP Recyclers

3.1 What is the average energy consumption of recycling 1 tonne of each type of FRP wastes?

____
____
____
____

3.2 Please rank the sustainability measures your company would like to undertake during recycling FRP wastes to reduce the energy consumption (1 being most preferred and 5 being least preferred). If you have already applied any of these measures, please tick the box instead of ranking.

- □ Energy Efficiency Improvements via upgrade equipment or techniques
- □ Renewable Energy Sources, such as solar or wind Power

- ☐ Process Optimisation with capturing and reusing waste heat generated during recycling processes for heating or other energy needs
- ☐ Streamline supply chain logistics to reduce energy consumption in transportation and distribution
- ☐ Apply the statics analysis to seek the improvement, such as conducting LCAs to identify energy hotspots in production and seek improvements.
- ☐ Other, please specific in below

3.3 Approximately how much waste is generated per unit for recycling FRP wastes?

- ○ Less than 1%
- ○ 1–5%
- ○ 6–10%
- ○ 11–20%
- ○ More than 20%

3.4 How many tonnes of all your products were generated during the recycling process in the financial year of 2020, 2021, 2023 and 2024?

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Section 4: Recycling Market Dynamics: Drivers, Restraints, and Circular Economic Practices

4.1 Please rank the recycling market drivers you consider most important, from 1 (most important) to 5 (least important).

- ☐ Growing accumulation of composite waste
- ☐ Government regulation and support
- ☐ Customer preference for sustainable materials
- ☐ Closing the product lifecycle loop (reusing waste generated during production and end of service life to achieve cost-effectiveness)

☐ Other (please specify): ____

4.2 Please rank the recycling market restraints you consider most important, from 1 (most important) to 8 (least important).

- ☐ Landfilling or incineration is easier for businesses
- ☐ Current recycling techniques require high investment
- ☐ Lack of comprehensive evaluation of different recycling techniques, making decisions difficult
- ☐ Operational complexity of current recycling methods
- ☐ Lack of regulation around disposal of FRP composites
- ☐ Lack of market for recycled products
- ☐ Recycled product quality does not meet buyer requirements or standards for remanufacturing (e.g., recovered fibres' mechanical properties are lower than virgin fibres)
- ☐ Other (please specify): ____

4.3 What are the main challenges your company faces in managing FRP waste?

- ○ Lack of local recycling facilities
- ○ High cost of transportation to recycling facilities
- ○ Limited choices of recycling technologies
- ○ Issues related to storage and transportation
- ○ Other, please specific in below

4.4 In what ways can researchers or recyclers contribute to addressing the primary waste management challenge you selected above?

- ○ Develop new recycling technologies
- ○ Provide technical guidance for waste processing based on current recycling methods
- ○ Establish an accessible platform to facilitate real-time collaboration between industry stakeholders, recyclers and academia for resource recovery
- ○ Distribute a white paper or report that incorporates cost-benefit analysis and life cycle assessments to evaluate economic performance and environmental impact
- ○ Provide regular consulting services for compliance with environmental regulations, such as twice a year

- Provide the training programmes for waste management personnel
- Establish pilot projects to demonstrate recycling solutions and investigate the integration of circular economy principles into waste handling processes tailored to your company's specific situation
- Other, please specific in below

4.5 What level of contribution can you provide to researchers or recyclers to support their efforts in addressing the waste management challenge you are facing?

- Financial contributions (cash support)
- In-kind contributions
- A combination of financial and in-kind contributions
- Other, please specific in below

4.6 How urgently do you expect researchers or recyclers to begin addressing the waste management challenge you are facing?

- Short period (within two months)
- Moderate period (within six months)
- Longer period (within one or two year)
- Not urgent (over 2 years)
- No specific timeframe

4.7 If applicable, what waste management issues are you and other companies or research institutions facing that are similar to the challenges you are currently experiencing? Please provide examples of how these entities have addressed these issues and the solutions they have implemented.

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4.8 What challenges or limitations have you found when using recycled materials? (Multiple choices available.)

- Quality consistency
- Supply chain issues
- Higher costs
- Regulatory compliance

- ○ Market acceptance
- ○ Other (please specify): ____

4.9 Do you think there will be an increased proportion of recycled materials in your FRP products in the next five years?

- ○ Yes
- ○ No

4.10 Is your company exploring any new technologies or processes to enhance the use of recycled materials in FRP products?

- ○ Yes
- ○ No

4.11 What financial incentives or in-kind support mechanisms would encourage your organisation to adopt more circular economy practices in fibre-reinforced polymer (FRP) recycling?

- ○ Grants or subsidies for recycling initiatives
- ○ Tax incentives for adopting sustainable practices
- ○ Financial support for the development of recycling technologies
- ○ Partnerships with researchers for technical expertise and resources
- ○ Broad market acceptance of recycled materials at reduced costs
- ○ Collaboration with other industries for shared resources and knowledge
- ○ Developed a 3-in-1 program for companies that encompasses production, research, and recycling, showcasing leadership in circular economy practices
- ○ Other, please specific in below

4.12 Would you please provide a case study related to your current waste management practices and sustainable initiatives?

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End of Survey

Thanks again for your participation.

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Abstract: The global push towards sustainable materials management and circular economies poses challenges for the composites industry. This project is addressing a critical unmet need in Australia's industry, namely, the sustainable recycling of Fibre-Reinforced Polymer (FRP) composites. FRP composites are seeing an increased use by several industries including aerospace, automotive, construction, and renewable energy, due to their high strength-to-weight ratio, corrosion resistance, and durability. Great as this is for Australia's composites manufacturing industry, it also poses a potential environmental and economic challenge – sustainable waste management. This project is conducting a comprehensive market analysis of the recycling potential of FRP composite materials in Australia, in the hope the research will pave the way for viable FRP composite recycling solutions. The project outputs are expected to benefit composite manufacturers, environmental agencies, and end-users by offering valuable insights into recycling processes, circular design and reuse, waste reduction, and the shift toward environmentally responsible practices, contributing to a greener and more sustainable future. Notably, its aims align with the United Nations (UN) Sustainable Development Goals, and reinforce Australia's Net Zero emission targets.	
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