A low-carbon pathway for proppants production using solid waste recycling

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Abstract

The growing need for sustainable hydraulic fracturing requires the development of proppants that align operational efficiency with environmental management. This paper analyses advances in low-carbon propping technologies, such as ultra-low-density proppants (ULDPs), multifunctional proppants, and traditional ceramic proppants. Integrating industrial by-products such as fly ash, slag, and drilling cuttings has resulted in substantial energy and carbon emissions savings. For example, microwave sintering techniques reduced energy consumption by 30%, while life cycle CO_2 emissions were reduced by 55% to 68% compared to conventional proppants. Mechanical tests confirm that these alternative promoters meet API standards for closing stress at 52 MPa, with a crushing resistance of ≤ 8% and a fracture conductivity of more than 90%, aided by self-healing coatings. In addition, non-combustion methods, including geopolymerisation and additive sintering, have allowed temperature reductions of up to 300ºC. This enhances the sustainability of fuel production. Despite these promising advances, challenges remain in standardising feedstock quality and adapting to evolving regulatory frameworks. However, the annual conversion of 1.1 billion tonnes of industrial by-products into high-performance proppants offers an opportunity for decarbonisation. To achieve this potential, we must continue to address critical gaps in field validation and standardisation of life cycle assessment. This underlines the need for interdisciplinary collaboration to integrate circular economy principles into unconventional resource extraction practices.

Keywords: Proppants, Sustainable Hydraulic Fracturing, Low-Carbon Technologies, Solid Waste Utilization, Environmental Impact

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Introduction

Hydraulic fracturing (fracking) has significantly enhanced hydrocarbon production from low-permeability reservoirs, making previously inaccessible shale formations viable for exploitation [1, 2]. However, it is important to highlight specific concerns regarding the use of natural resources, such as quartz sand. Over-exploitation of these resources can lead to ecological damage, including habitat destruction and increased silica dust pollution, which further exacerbates environmental and health risks [3, 4]. Central to this technology are proppants, granular materials such as silica sand or ceramic particles, that maintain fracture permeability by preventing fracture closure after the injection of high-pressure fluids. Despite their effectiveness, traditional proppant manufacturing consumes intensive energy, primarily due to high-temperature sintering processes and resource-intensive mining operations [5, 6]. Consequently, conventional proppant production contributes substantially to global carbon emissions, habitat destruction, and water contamination risks, all representing urgent environmental concerns [7, 8]. The global proppant market, as shown in Figure 1, is projected to expand from USD 9.1 billion in 2023 to approximately USD 15.6 billion by 2030 at a compound annual growth rate (CAGR) of 8%, underscoring the critical need for more sustainable production practices [9, 10]. Thus, the traditional proppants, notably ceramics manufactured at temperatures over 1300°C, generate around 0.8-1.2 tons of CO_2 per ton of product, while silica sand extraction exacerbates ecological problems and silica dust pollution [11, 12]. Additionally, regulatory attention has risen over the environmental concerns of fracturing fluids, specifically involving chemical spills and damaged health integrity [13, 14].

To mitigate these problems, industrial solid waste, including fly ash, slag, and drilling cuttings, is increasingly favoured as an alternative raw propulsion material. Flying ash, resulting from coal burning, and slag, the remains of the steel industry, offer distinct advantages because of their aluminosilicate composition, which facilitates geopolymerisation and reduces the need for high-temperature sintering [15, 16]. Nevertheless, fluctuations in waste composition, contamination risks and scalability challenges hinder widespread use. Progress in modifying particle surfaces and designing hybrid materials, such as integrating fly ash with resin coatings, is being made to overcome these stresses [17, 18].

The characteristics of regional markets further facilitate the transition to sustainable practices. For example, North America accounts for about 45.6% of global shale gas consumption, reflecting its significant shale gas activities [19-21]. The industry is under increasing pressure to adopt strategies that meet decarbonisation objectives while maintaining operational efficiency [22, 23]. Recent advances, such as Smart Sand's use of low-density proppants and optimised supply chain methodologies, demonstrate initiatives to reduce environmental effects by reducing chemical use and controlling quantities [24, 25]. Nevertheless, significant barriers remain, such as inconsistent quality of waste produced by the proppant, disjoint regulatory frameworks and insufficient validation of innovative technologies in the field [26].

This review aims to critically assess emerging sustainable alternatives to conventional proppants, providing a comprehensive, helpful analysis for environmental scientists, engineers and policymakers. It synthesises existing fragmented literature across critical areas of investigation: identification and evaluation of novel proppant materials, such as ultra-lightweight and multifunctional proppants; comparative assessment of environmental impacts between conventional and waste-derived proppants; development of optimised strategies for the utilisation of solid industrial wastes, such as fly ash and slag; improvement of energy efficiency in proppant manufacturing processes by reducing sintering temperatures; exploration of non-combustion-based geopolymerisation methods; and complete evaluation of low-carbon proppants from mechanical, economic, and lifecycle perspectives. By integrating field validation data, and regulatory compliance assessments, this review clarifies current advancements and establish guidelines that balance industrial growth with environmental sustainability in hydraulic fracturing operations.

Advances in Hydraulic fracturing Proppants

Technological advances in hydraulic fracturing proppants are crucial in improving operational efficiency and reducing the environmental impacts of hydrocarbon extraction [27, 28]. This progress is based on innovative materials, as Figure 2 illustrates, such as ultra-lightweight proppants, multifunctional proppants, traditional proppants, surface modification techniques, in-situ generation methods, and cutting-edge techniques that meet the industry's current challenges [29].

Significant innovations include Ultra-Lightweight proppants (ULDPs), which are characterised by their integration of light and mechanical energy. These materials are produced from industrial by-products like fly ash, providing a cost-effective alternative to traditional ceramic proppants, illustrated in Figure 2 [30, 31]. Their regulated porosity configurations enable hydrophobic discharge, making them suitable for various fracture conditions [32]. Laboratory experiments have verified that even at pressures greater than 20 MPa, these materials maintain good conductivity while reducing logistical costs [33]. The creation of multifunctional support materials is a significant advancement in the field. These materials have complementary functionality, e.g., piezoelectric sensors that monitor fracture geometries in real-time, optimising production. Their interconnected porosity also facilitates the transport of stimulating fluids or the capture of CO_2 during extraction. Besides, elastomer coatings facilitate self-healing, minimise proppant losses, and increase healthy life [34].

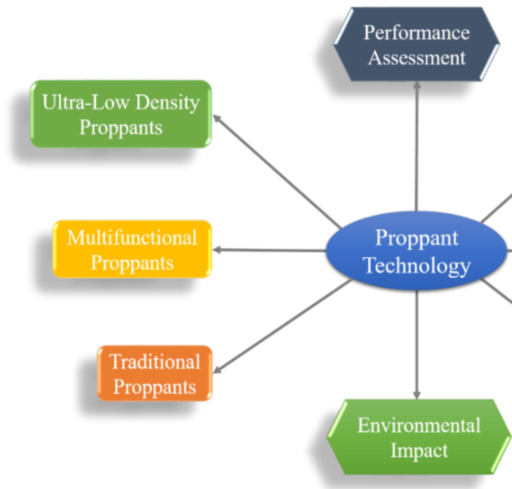

Figure 1. Fracturing Innovations and Enhancements in Proppant Technology for Hydraulic Fracturing

Sustainability lies at the centre of the concerns, particularly with the application of industrial waste in manufacturing proppants [35]. It lowers carbon emissions and costs. Research indicates that these materials achieve 90% of the strength of ceramic proppants at half the price. [36, 37] However, their variability in particle size requires more excellent standards for large-scale uses [38, 39]. New surface techniques, such as liquid modification, allow proppants to adhere to fracture walls more efficiently, reducing the migration of fines by half. Shape memory polymers (SMP) expand according to temperature or pressure changes. This property closes cracks naturally, thereby providing the highest conductivity [40, 41]. Additionally, chemical reactions such as those in sol-gel systems enable the formation of proppants in the tank itself, a process termed "in situ generation." The method reduces transport costs and has increased conductivity by 30% in complex geology [42].

To manage these operations, high-temperature neutron capture techniques and magnetic nanoparticles provide accurate 3D representations of fractures, minimising non-productive zones to a bare minimum. Lastly, these technologies represent a significant step towards more efficient and environmentally friendlier technologies. There are challenges, however, particularly concerning material stability under stress that can be as great as tens of MPa and standardisation of procedures.

Traditional ceramic proppant production

Ceramic proppants are essential in hydraulic fracturing, a method employed for the extraction of oil and gas. They preserve the fracture aperture, hence facilitating optimal fluid flow [43]. They are conventionally composed of high-purity aluminosilicates, such as bauxite and kaolin. Bauxite, infused with alumina, has significant resistance to crushing, whereas kaolin, upon sintering, converts into mullite, a phase noted for its resilience under subterranean conditions [44, 45]. Complete treatment of these raw materials, including particle formation and high-temperature sintering, is essential to achieve mechanical and chemical properties. Conventional sintering procedures, requiring temperatures between 1150°C and 1590°C and periods ranging from 75 minutes to 10 hours, pose considerable problems [46, 47]. High thermal regimes, although essential for chemical transformation and densification, require significant energy expenditure, resulting in increased production costs and environmental effects of carbon emissions [36, 48]. In addition, prolonged exposure to high temperatures can trigger unregulated granular development, which can compromise microstructural integrity and, subsequently, the mechanical performance of proppant materials [49].

Recent research has focused on modifying compositions to reduce sintering temperatures. One viable method is to incorporate solid waste into proprietary formulations, such as industrial by-products and recovered mineral residues [50]. These additives, often consisting of alkali or alkaline earth oxides such as CaO, Fe_2O_3, and MgO, act as fluxes [51]. During thermal treatment, these components lower the viscosity of the aluminosilicate melt, thereby enhancing liquid-phase sintering and promoting particle reorganisation at lower temperatures. Furthermore, verifiable oxides found in specific wastes facilitate the formation of transient eutectic phases, thus accelerating densification kinetics and reducing energy consumption [52, 53]. This method improves process sustainability by valorising waste streams while simultaneously refining the microstructure of proppant materials, thereby decreasing porosity and increasing fracture resistance [54].

Research highlights the efficacy of this method. The incorporation of fly ash, abundant in alkaline oxides, has demonstrated efficacy in decreasing sintering temperatures by lowering the eutectic temperature of the ceramic mixture [31, 55]. Petroleum-based drilling and cutting pyrolysis residue (ODCPR) is effective in promoting low-temperature sintering, hence decreasing production costs and environmental impact [56]. The incorporation of carbon gangue has been investigated to lower preparation costs and sintering temperatures, yielding proppant materials with favorable densities and failure rates [57].

Overall, the judicious integration of solid waste additives in the production of ceramic proppant materials offers a viable solution to the challenges associated with high-temperature sintering. By leveraging the melting properties of these materials, the requisite mechanical and chemical attributes can be achieved at reduced thermal conditions, hence improving durability and profitability.

Benefice of Using Solid Waste Utilisation in Proppant Production

4.1 Types of Solid Waste Materials

Table 1 compares industrial solid wastes used in proppant production, focusing on fly ash, slag, and drill cuttings. Fly ash is notably cost-effective, achieving 90% of ceramic proppant strength at half the cost, thanks to its high SiO_2 (≥70%) and $Al2O_3$ (20-35%) content [58]. However, Fe_2O_3 levels must be lowered by 30% by advanced pre-treatment, including 5% HCl leaching for structural integrity. Drill cuttings also show promise as processing via pyrolysed calcium- and iron-rich residues improves the proppant strength by 15% in ODCPR-bauxite systems. While keeping awareness of cost and performance, these materials show good advantages for proppant manufacturing, as shown in Figure 2.

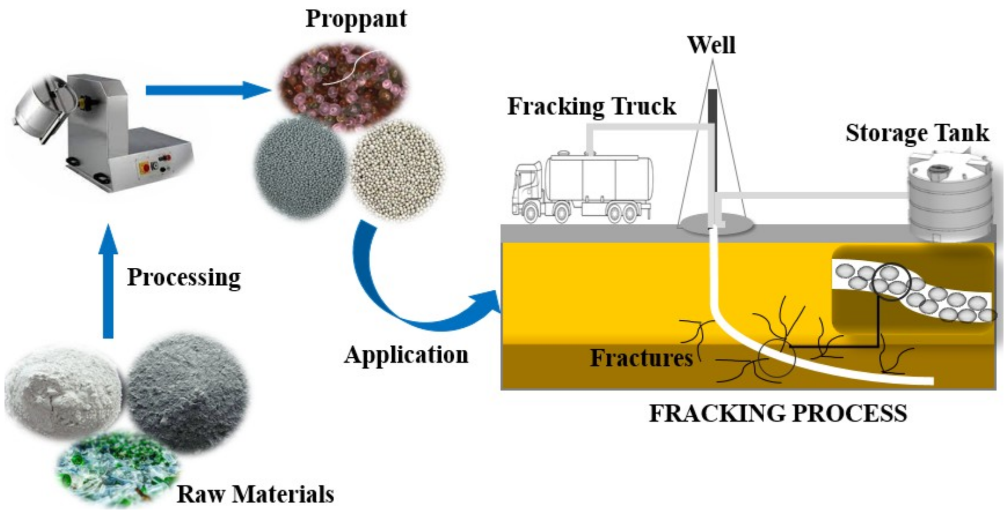

Figure 2. Integration of Solid Waste Materials into Proppants Manufacturing

Consider fly ash, for instance. The residue left after burning coal contains substances like silica and alumina. This material can create strong, lightweight ceramic proppants [59, 60]. Not only does this reduce our reliance on traditional materials, but it also helps to clean up the waste from coal power plants[61, 62]. Some studies indicate that fly ash rich in alumina can produce proppants that perform well in deep wells[50, 59]. Additionally, it may require less energy to manufacture them, which is good for everyone.

Then there are drill cuttings, those bits of rock that come up when it dries for oil and gas. They can be turned into something useful by heating them in pyrolysis [63, 64]. This process leaves behind materials like calcium oxide and iron oxide, which can make proppants stronger and less dense [59, 65]. The pyrolysis process costs money but is much better than dumping the cuttings and risking environmental harm problems [66, 67].

Slag, a by-product of steel production, is another object of investigation. Although it is not as widely used as fly ash or drill cuttings, several experimental initiatives have proven its effectiveness [11-13]. The considerable annual production of slag offers the possibility of using it as a proppant, thus supporting waste management [68]. But, as with other materials, ways must be found to make it more cost-effective and ensure consistent quality.

Even old glass is being considered! Recycling glass into proppants could help reduce the amount of waste in landfills and transform ordinary waste into a useful material. The only issue is that turning glass into proppants takes a lot of energy, so we need to find ways to make that process cheaper [69, 70]. The only issue is that turning glass into proppants takes a lot of energy, so we need to find ways to make that process cheaper [71, 72].

Table 1. Comparison of Solid Waste Materials as Alternative Proppant Raw Materials

Waste Type	Source Industry	Key Properties	Proppant Application	Challenges	Ref
Fly Ash	**Coal Power Plants**	**High silica and alumina content**	**Lightweight, high-strength ceramic proppants**	**Availability varies by region**	**[73-75]**
Drill Cuttings	**Oil and Gas Drilling**	**Rock fragments, variable composition**	**Ceramic proppants, especially ODCPRs**	**Processing complexity, environmental concerns**	**[76, 77]**
Slag	**Steel Production**	**Metal oxides, silicon dioxide**	**Potential proppant, less common**	**High processing costs, consistency issues**	**[54, 78]**
Rice Husk Ash	**Agriculture (Rice Processing)**	**High in silica, light, and porous.**	**Lower compressive strength, needs binder.**	**Inconsistent material properties and mechanical strength.**	**[79, 80]**
Wood Ash	**Biomass (Wood Burning)**	**Contains silica, calcium, potassium, and magnesium. Varies depending on the wood type.**	**Lightweight, can be used in certain low-strength applications.**	**High variability, requires reinforcement, lower mechanical strength.**	**[81]**
Glass Waste	**Municipal, Industrial**	**Silica-rich, recyclable**	**Synthetic proppants**	**Energy-intensive processing**	**[50, 57, 69]**

Lastly, using spent Cu-based oxygen carriers, leftovers from copper industries, is still pretty new. Still, they might help make ceramic proppants better by lowering the temperature needed [74, 77].

Overall, utilising waste materials to produce proppants is a commendable initiative that benefits the environment and has the potential for cost savings. However, challenges remain, such as reducing production costs and ensuring material consistency.

4.2 Preparation Processes

The effective incorporation of industrial by-products, as outlined in Figure 3, into proppant manufacturing necessitates a meticulously structured preparation methodology to ensure adherence to stringent hydraulic fracturing performance criteria. This methodology comprises a series of sequential operational phases, including feedstock selection [82, 83] and characterisation, preliminary processing and particle size adjustment [36], binder formulation and integration [84], shaping techniques, thermal processing, and a comprehensive evaluation of performance and sustainability, each contributing to the development of high-efficacy, environmentally responsible proppants.

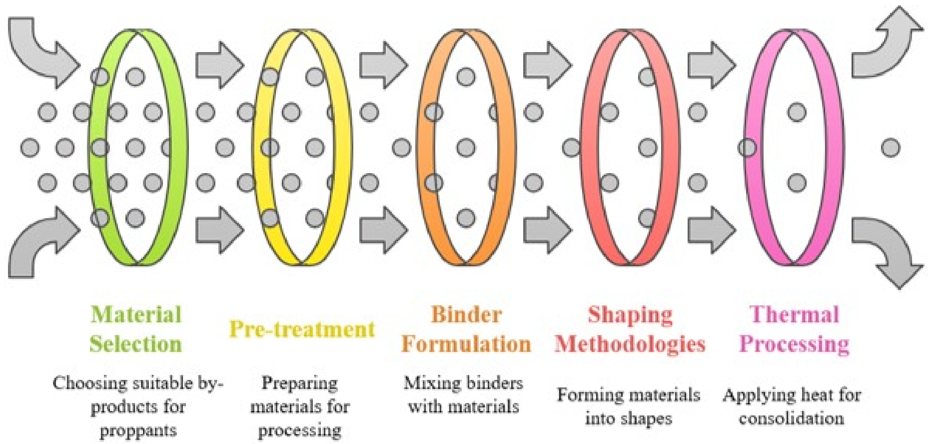

Figure 3. Incorporation of industrial by-products for proppants production

Material Selections and Characterization

Industrial solid waste streams, particularly fly ash and bauxite residues, are recognised as prime prospects for proppant synthesis due to their intrinsic silica (SiO_2) and alumina (Al_2O_3) content, aligning with critical proppant performance metrics. For instance, fly ash with elevated SiO_2 concentration (≥70%) improves crush resistance in proppants, as evidenced by its application in ceramic proppant cores integrated with clay and bauxite coatings. Coal mining refuse, abundant in SiO_2 and Al_2O_3, meets the compositional criteria for mullite-based proppants; nonetheless, the cited sources primarily emphasise fly ash and bauxite mixtures [85].

Advanced analytical techniques, including X-ray fluorescence (XRF) and X-ray diffraction (XRD), are essential for characterising these materials. Research on fly ash activation underscores the significance of XRD in detecting crystallographic alterations during alkali treatment [85, 86]. XRF is employed to quantify the elemental composition of waste-derived geopolymers and zeolites [87]. The phase composition of fly ash (amorphous versus crystalline) directly influences its appropriateness for proppant production [88].

Pre-treatment and Particle Sizing Control

The preliminary processing of solid waste materials is essential to enhance their viability for proppant production, as illustrated in Figure 4. Various crushing and grinding methods are employed to achieve a consistent particle size distribution, usually under 75 µm, which also boosts reactivity during subsequent thermal treatment [89]. For instance, studies on ceramic proppants often involve sintering processes that benefit from uniform particle sizes [90].

Techniques such as magnetic separation and acid leaching remove impurities, including unburned carbon and heavy metals, that may jeopardise the proppant's structural integrity as mentioned in Figure 5 [57]. For example, applying a 5% hydrochloric acid (HCl) solution to fly ash led to a 30% reduction in iron oxide (Fe_2O_3) content, hence alleviating undesirable crystallisation during heating [91].

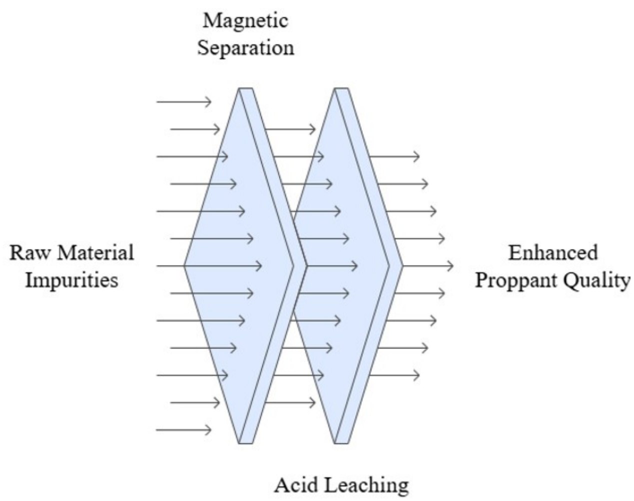

Figure 4. Purification Process for Proppants Enhancement

Including binding agents such as sodium silicate or kaolin in quantities of 10 to 20 weight percent improves the material's plasticity, facilitating pellet formation via extrusion or granulation [92, 93]. Using binding agents is a common practice in ceramics and materials science.

Due to the inherent unpredictability of waste material composition, flexible mixing ratios and real-time monitoring technology are essential to ensure process uniformity [77].

Binder Formulation and Homogenization

Integrating binder systems is essential for improving the mechanical integrity of proppants formed from waste materials. Binder systems, including sodium silicate or geopolymer precursors, promote the creation of cohesive pellets, as illustrated in Figure 5. For instance, geopolymer binders can be sourced from natural or synthetic aluminosilicates, and the process involves a chemical reaction between aluminosilicate oxides and alkali polysilicates, resulting in the formation of polymeric (Si-O-Al) bonds and amorphous to semi-crystalline structures [94]. This process is crucial for enhancing the infrastructure system's sustainability and economic viability by utilising waste materials and reducing carbon dioxide emissions.

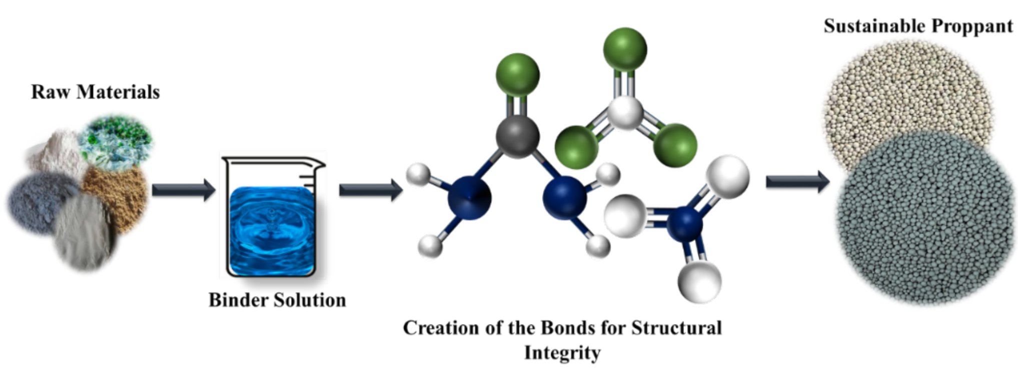

Figure 5. Binder System Integration for Proppants Manufacturing

Studies have shown that adding 5-10 wt% nano-clay to coal mining refuse can enhance interfacial bonding and diminish brittleness, as presented in Figure 4, yielding proppants with superior mechanical properties [65, 95]. For example, using nanoparticles in various applications, such as hydraulic fracturing, has been explored to improve performance [96]. High-shear mixing under optimised conditions ensures the creation of a homogenous slurry, which is critical for achieving uniform proppant morphology [95]. This process is vital for ensuring that the proppants have consistent properties, which are essential for their application in hydraulic fracturing [97].

The principles of using binder systems, enhancing mechanical properties with additives, and ensuring uniform morphology through mixing conditions are well-established in materials [98].

Shaping Methodologies

Proppant fabrication from industrial waste streams encompasses several methodologies, including extrusion, palletisation, and additive manufacturing [57]. Frequently employed with spray drying, rotary granulation has emerged as a scalable technique for producing spherical particles, exhibiting a diameter variability of less than 5% [99, 100]. This increased homogeneity enhances efficiency in hydraulic fracturing operations [101]. Additive manufacturing techniques, particularly 3D printing, are being explored to create proppant shapes customised for specific operational needs [102]. Customised designs have the potential for increased mechanical strength and enhanced flowback management during fracturing operations [103].

These advanced manufacturing techniques facilitate the use of diverse industrial waste materials, including fly ash and lower-grade bauxite, in producing high-performance proppants characterised by reduced density and augmented strength [53]. Using such waste products helps reduce the need for raw materials and creates a more sustainable method of proppant production [40, 56].

Thermal Processing and Consolidation

The sintering process, a heat-activated densification mechanism, is essential to improve the resistance and performance of the proppant [59]. Conventional sintering consists of heating proppants to 1100-1300°C, allowing reinforcement phases such as mullite in formulations based on fly ash [104, 105]. This procedure enables compression resistors above 52 MPa, with regulated cooling (2-5°C/min) crucial to prevent thermal cracking [106, 107].

Microwave sintering, an emerging alternative, demonstrated energy savings of 30% compared to conventional methods in experimental environments [108, 109]. Although promising for its efficiency and reduced environmental impact, this technology remains on track for proppant production, with most industrial applications still dependent on established thermal methods [110]. Non-sintering approaches, such as inorganic polymer proppants, use chemical bonding to obtain light, high-strength structures without high-temperature treatment [110, 111].

Surface modification approaches, including chemical or pressure-assisted bonding, enhance proppant cohesiveness [36]. These methods often use pressure or chemicals to hold the proppants together [112]. However, heat-treated proppants remain dominant because of their better mechanical properties [113]. Overall, whereas conventional sintering remains the industry standard for high-performance applications, alternatives like microwave and non-sintering techniques may provide sustainability advantages. Nonetheless, these ideas require further validation to attain a balance between efficiency, and scalability [84].

In short, heating is a key step in making proppants strong, but making them without heating is another method that might have some advantages and challenges.

Performance and Sustainability Assessment

Scientists use advanced testing procedures to determine the viability of waste materials, such as slag and fly ash, for hydraulic fracturing [84]. These thorough evaluations focus on the proppant's essential qualities, such as strength, roundness, and pressure resistance [54]. According to research, proppants made from recycled materials frequently match or outperform standard proppants while providing additional environmental benefits. This novel strategy improves hydraulic fracturing efficiency and supports industrial sustainability [31].

There are two main ways to make these proppants. One way is called thermal consolidation (sintering). This means heating the waste materials but not melting them. This makes them strong and lasts a long time. For example, glass-ceramic proppants, which are noted for their superior mechanical qualities, can be manufactured by sinter-crystallization of recycled materials [114]. The other way is called the non-sintered method. This means using the waste materials without heating them so much [111]. However, most studies focus on thermal consolidation because it usually makes stronger proppants.

Searchers use a lifecycle analysis to see how suitable these proppants are for the environment. This allows to determine the energy consumption, the amount of pollution generated and the amount of resources needed for the production of the proppants [36, 115, 116]. It is essential to know that using waste materials can reduce pollution by up to 30% [117]. Also, because of the possibility of recycling these proppants, they are even better for the environment in the long run. So, using waste to make proppants is a good way to save resources and reduce pollution.

Lowering Sintering Temperatures through Additive Incorporation

Sintering is a vital step in proppant manufacturing, traditionally requiring high temperatures (1100-1400°C) to impart mechanical strength for hydraulic fracturing operations [104, 118]. High temperatures, however, translate into high energy usage, causing carbon emissions and operational expenses [119, 120]. Recent advances demonstrate that the strategic application of additives makes reducing sintering temperatures by 100-300°C (considering room temperature ±23°C) possible with equal or better mechanical performance, such as catalogued in Table 2 [69, 71]. This approach aligns with circular economy and sustainable development principles, offering a means to cleaner and cheaper proppant manufacturing.

Use of Additives in Temperature Reduction

Research indicates that sintering additives (Table 2) play a crucial role in lowering the processing temperatures of ceramic proppants while maintaining their mechanical properties, thereby promoting energy conservation and the recycling of industrial waste. The additives operate primarily via three mechanisms: forming a liquid phase, optimisation of particle size, and the effects of synergistic fluxing [121-123]. Below are the main categories of additives and their contributions.

Fluxing agents, such as calcium carbonate ($CaCO_3$) and feldspar, reduce sintering temperatures by promoting liquid phase sintering, as shown in Table 2. For example, 5% by weight of $CaCO_3$ reduces the sintering temperature to 1350°C (a reduction of 150°C) in bauxite-based proppants, reaching fracture levels below 8.5% at 52 MPa. The feldspar, comprising 4% by weight, helps sintering at 1400° C., resulting in a temperature reduction of 100° C. With optimised milling, sintering can occur at 1280° C., reducing 220° C. These additives improve densification while maintaining strength, aligning with sustainability-oriented manufacturing objectives.

Additives such as dolomite and fly ash allow sintering at low temperatures by promoting the formation of mullite or corundum. Dolomite ($MgCa(CO_3)_2$) combined with fly ash fritters and bauxite efficiently at 1200°C (reduction of 300°C), resulting in a mullite-corundum complex with acceptable mechanical properties. Flying ash, acting both as raw material and flux, facilitates the crystallisation of mullite at 1200° C. These approaches not only reduce energy demand but also value industrial by-products.

Industrial waste, such as pyrolysis residues (ODCPR) and oil-based pyrolysis, offers two advantages. Manganese dioxide (MnO_2) in ODCPR-bauxite mixtures allows for frying at 1280° C. (reduction of 220°C.), producing low-density (<2.7 g/cm^3) and high-strength proppants. Pyrolusite (20% by weight) reduces the sintering temperature of quartz-based proppants from 900°C to 400°C to 500°C, thus facilitating consolidation at low temperatures.

Metallic oxides, such as CaO and FeO in ODCPR, improve fluxion by chemical activity. Multi-component systems further amplify temperature reduction. For example, a combination of $Al_2 O_3$ (5% by weight), cap glass (20% by weight) and NaF (4% by weight) reduces sintering temperatures to 1100°C (a reduction of 400 to 500°C) in drill cuttings-based trousers. [124-126].

Effective sintered additives aim to reduce temperatures through shared mechanisms: (1) liquid formation, (2) particle size optimisation and (3) liquid agent combination. $CaCO_3$, field spar and MnO_2 promise to reduce 100-150°C while maintaining brewing performance. Combine additives or internal flow properties (e.g. ODCPR, flight gas) to combine waste up to 1200 °C sintered, thereby achieving the sustainability objectives of ceramic thruster production.

Table 2. Additives for Lowering Sintering Temperature

Additive(s)	**Proppant Material(s)**	**Sintering Temperature (°C)**	**Temperature Reduction (°C) (Approx.)**	**Ref**
Calcium Carbonate (5 wt%)	**Natural bauxite, solid waste coal gangue**	**1350**	**150**	**[122, 127]**
Feldspar (4 wt%)	**Bauxite**	**1400**	**100**	**[128, 129]**
Feldspar (Optimised Milling)	**Bauxite**	**1280**	**220**	**[130]**
Manganese Dioxide (With ODCPRs & Bauxite)	**ODCPRs, Bauxite**	**1280**	**220**	**[131]**
Vanadium Pentoxide (With ODCPRs & Bauxite)	**ODCPRs, Bauxite**	**(Implied Lower)**	**-**	**[127]**
Dolomite (with Fly Ash & Bauxite)	**Fly Ash, Bauxite**	**1200**	**300**	**[132]**
Al_2O_3, Cullet Glass, NaF (with Drill Cuttings)	**Drill Cuttings**	**1100**	**400-500**	**[133]**
Pyrolusite (20%)	**Solid waste silica fume (Quartz Ceramic Proppant)**	**900**	**400-700**	**[134]**
CaO, BaO, MgO, FeO (from ODCPRs)	**(Implied with Bauxite)**	**(Implied Lower)**	**-**	**[127]**

Additive combinations take advantage of complementary flow and densification processes, significantly improving energy efficiency and sustainability. Table 2 clearly shows the specific results associated with each category of additives, showing how these unique formulations reach temperatures below the conventional sintering range of 1300 to 1600°C. Additive selection depends on their interactions with the base material, while sustainability initiatives focus on integrating waste-derived resources and energy-saving practices. This approach not only improves performance but also promotes environmentally friendly manufacturing.

Use of solid waste in temperature reduction

In the production of ceramic proppants, it is crucial to lower sintering temperatures to enhance energy efficiency and boost material performance. Although conventional mixtures are essential in this process, the integration of diverse solid waste has emerged as a practical alternative [135, 136]. Many studies have shown that these wastes significantly contribute to lower sintering temperatures, resulting in economic and environmental benefits. Among the effective solid waste, fly ash stands out as a candidate of choice [137]. This by-product, which is the product of coal burning in power plants, contains high concentrations of silica and alumina. Research indicates that integrating fly ash into proppant formulations can reduce the required sintering temperature [138].

Moreover, proppants formulated with fly ash have desirable mechanical properties and often have performance characteristics that satisfy or exceed those of traditionally produced materials. The coal gangue also emerges as a solid waste promising for proppant production [139, 140]. As a by-product of coal mining operations, the coal gangue has a favourable chemical composition that allows it to replace bauxite in propelling formulations [141]. Manufacturers can achieve substantial savings using the coal gang while reducing sintering temperatures. This dual advantage underscores the importance of exploring alternative materials to improve resource efficiency within the industry [142].

Furthermore, the ash of the rice hull, created from the burning of the rice bark, offers essential advantages in producing proppant. Enriched with silica, rice shell ash can effectively reduce sintering temperatures while improving the physical properties of the ceramic material [73, 143]. This strategy is attractive because it promotes increased profits and sustainable agricultural waste management while supporting our broader environmental goals. It's worth noting that bauxite waste, a by-product of alumina mining, offers a fantastic way to reduce temperatures in proppant production.

Research indicates that including bauxite waste in proppant formulations lowers sintering temperatures while maintaining the structural integrity of the final product. These tailings significantly reduce the environmental impact of bauxite mining while actively promoting the recycling of industrial by-products [11, 144]. The careful incorporation of solid wastes into ceramic applications tells you that the flying tips, the charcoal rod, the rib tip tips and the bauxite tips considerably reduce the frying temperatures. This process improves the effectiveness of environmental defences entirely in favour of activities that reduce energy consumption and consumption to a minimum [145, 146]. The literature strongly supports the approach, highlighting are powerful and considerable impact to improve the durability of the ceramics proppants production.

Mechanisms of Sintering Additives

Sintering additives lower the thermal energy required for ceramic proppant densification through three interrelated mechanisms: liquid-phase formation, enhanced solid-state diffusion, and surface energy modification. The interplay of these mechanisms enables energy-efficient production while maintaining mechanical performance, though trade-offs between additive efficacy and proppant properties necessitate careful optimisation, as explained in Figure 6 [135].

The most often-used method employs additives to generate transient liquid phases at low temperatures, allowing particle rearranging and pore elimination [147]. In bauxite-coal gangue systems, for example, $CaCO_3$ breaks down into CaO by the use of low-melting eutectic liquid produced by interactions between silica and alumina [148]. This phase facilitates sintering at 1350°C-150°C below additive-free formulations while maintaining a breakage ratio of 8.41% under 52 MPa closure pressure [149]. Likewise, feldspar's low melting point (~1100°C) generates a viscous glassy phase that envelops bauxite particles, diminishing interfacial energy and facilitating sintering at 1280 °C when paired with refined milling techniques. Manganese dioxide (MnO_2) illustrates this mechanism by dissolving into the corundum lattice, resulting in lattice distortions and the formation of low-viscosity melts (e.g., anorthite, $CaAl_2Si_2O_8$) that improve densification in ODCPR-bauxite systems at 1280°C [150]. The effectiveness of these additives is fundamentally influenced by the wettability and viscosity of the liquid phase, which determine pore clearance kinetics and the resultant microstructure [151].

Although secondary to liquid-phase effects, specific additives enhance ion mobility in the solid state, especially during the last stages of sintering. MnO_2, as explained briefly in Figure 6, for example, incorporates Mn^{4+} ions into the corundum lattice, creating oxygen vacancies that facilitate the diffusion of Al^{3+} and O^{2-} ions. While less common than liquid-phase methods, diffusion enhancement is crucial in improving microstructural homogeneity by utilising partial melts. In Al_2O_3-cullet glass systems, sodium fluoride (NaF) effectively reduces diffusion activation energy, reinforcing grain boundaries without needing full liquid-phase saturation [152, 153].

Additionally, feldspar and cullet glass serve as fluxes that significantly lower the surface energy of ceramic particles, leading to improved bonding at lower temperatures. This process enhances overall material performance and stability. Below normal sintering conditions, Feldspar reduces the interfacial tension between bauxite particles and molten phases, enabling neck development at temperatures ranging from 1400 °C to 100 °C. Systems with restricted liquid-phase formation, where atomic-scale surface contacts predominate early-stage densification, depend mainly on this mechanism [154, 155].

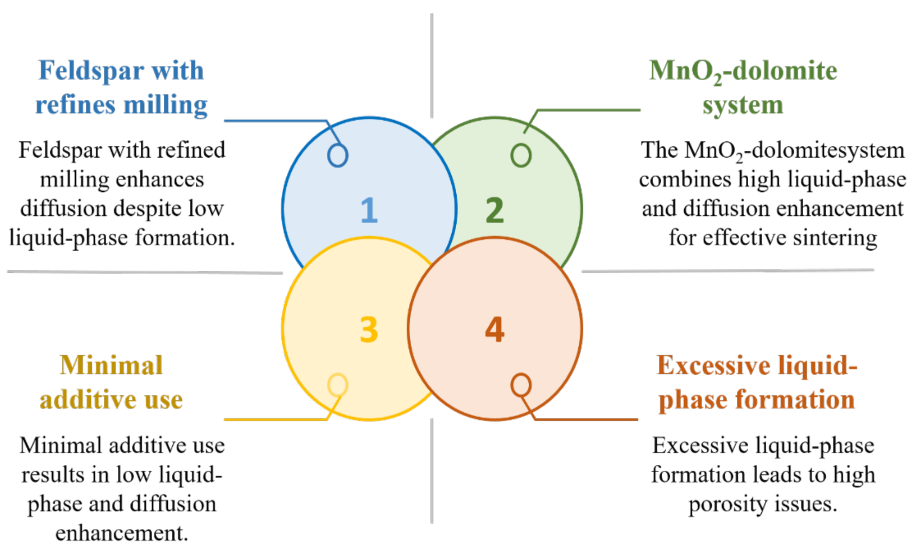

Figure 6. Optimisation Sintering Additives for Ceramic Proppants

Combining additives often produces better results using synergistic reactions. This is illustrated in fly ash-bauxite proppants via the MnO_2-dolomite system [156]. While dolomite-derived MgO promotes mullite nucleation, which results in full densification at 1200 °C, MnO_2 facilitates liquid-phase sintering; likewise, by merging glass-mediated melting (cullet) with fluoride-enhanced diffusion (NaF), Al_2O_3, cullet glass, and NaF combinations lower sintering temperatures to 1100 °C [157]. Nonetheless, additive inclusion presents trade-offs. Excessive liquid phases might elevate porosity (e.g., >5 wt% $CaCO_3$ increases breaking ratios), whereas expensive additions such as V_2O_5 may negate energy benefits. Furthermore, the requirement of compositional optimisation is a factor in phase stability, particularly the anorthite produced by MnO_2 that influences acid resistance [158].

Effective sintering temperature reduction hinges on balancing liquid-phase formation, diffusion enhancement, and surface energy modification. Additives like $CaCO_3$, feldspar, and MnO_2 demonstrate robust performance in bauxite- and waste-derived systems, with synergistic combinations enabling sintering below 1200 °C [121].

Performance Evaluation of Non-Burning Proppants

Mechanical proppant strength is essential to hydraulic fracturing success as it directly affects fracture conductivity, toughness, and resistance to subsurface stress. Lo-carbon proppants, which have been engineered to lower carbon footprints without diminishing structural strength, share the same mechanical characteristics or superior ones compared to conventional proppants such as silica sand, resin-coated sands and ceramic products. Their compressive strength, crush resistance, and sphericity/roundness are tested and compared to industry standards and available market alternatives, as it is shown in Table 3 [159, 160].

Table 3. Comparative Mechanical Properties of Low-Carbon vs. Conventional Proppants

Property	Solid Waste-Based Proppants	Silica Sand	Resin-Coated Proppants	Ceramics	Ref.
Compressive Strength	**54 MPa**	**35-40 MPa**	**45-50 MPa**	**50-100 MPa**	**[161-163]**
Crush Resistance	**5.2% fines**	**14.8% fines**	**4.1-4.9% fines**	**<3% fines**	**[111, 163, 164]**
Sphericity	**0.92**	**0.65**	**0.85**	**0.95**	**[111, 162, 165]**
Density	**2.2 g/cm^3**	**2.65 g/cm^3**	**2.4-2.6 g/cm^3**	**3.2-3.8 g/cm^3**	

Proppants from by-products have unmet robust chemical stability, polymer coatings are reluctant to acid-induced mass loss to less than 5% after 72 hours of hydrochloric acid (HCl) exposure. The thermal degradation remains below 3% after 14 days at 150°C, aligning with the performance of high-end ceramics and ensuring durability under challenging tank conditions. Although the low-carbon proppants do not attest to the compressive strength of ultra-high-strength ceramic (70-100 MPa), they are out of reach of 40% of the carbon incorporated (1.2 kg eq/kg CO_2 compared to 2.5 kg eq/kg CO_2 for ceramics). Using recycled materials further improves their durability, making them a viable alternative without compromising operational efficiency. This balance impairs the objectives of decarbonisation in the extraction of hydrocarbons.

Balancing Strength and Sustainability Innovations in Proppant Materials

Recycling Waste from By-product to Layer High-Performance Proppants

The use of solid waste in manufacturing proppants is an eco-friendly approach to environmental and economic issues in hydraulic fracturing. While effective in maintaining fracture conductivity, traditional methods of producing proppants are environmentally degrading and wasteful. The mechanical properties of proppants can be enhanced by using industrial waste by-products like fly ash. Low-grade bauxite and fly ash proppants possess a bulk density of 1.352 g/cm^3 and a breakage ratio of 5.3% at 35 MPa pressure [166]. Similarly, Coal gangue low-density ceramic proppants perform best at 1400°C with a bulk density of 1.28 g/cm^3 and a breakage ratio of 7.89% at the pressure of 52 MPa [166].

However, heavy metal and organic compound waste material contaminants severely impact proppant performance and safety. Pre-treatment methods such as hydro-acoustic cavitation effectively remove contaminants. Still, they are expensive [167]. Emerging recycling technology, including fluidised bed reactors, has increased the mechanical integrity of proppants from wastes under optimised sintering conditions [168].

Though cost reductions are part of the situation when using waste feedstocks, problems are encountered, predominantly waste pre-treatment and quality control. Nevertheless, scientific studies prove that low-density proppants developed at reduced sintering temperatures can meet industrial demands with fewer preparation expenses [56]. Moreover, field-scale simulations demonstrate that optimal proppant pumping programs can potentially boost gas production by 8.2%.

Using solid waste in proppant production has economic and environmental benefits. By increasing recycling and supporting positive regulation, proppants from waste can help make hydraulic fracturing sustainable while being high-performance and low-cost.

Environmental Challenges of Proppant Production

Proppants are essential for hydraulic fracturing, but their manufacture poses environmental and health problems. To adapt to sustainability and economic objectives, a transition from low-carbon to high-carbon alternatives is required, as explained in Figures 7 & 8 [169, 170]. Traditional resin-coated proppants, for example, emit toxic compounds such as phenol and formaldehyde, resulting in groundwater contamination and the destabilisation of fracking fluids. Premature curing of resin coatings further reduces the conductivity of the fracture, compromising operational efficiency [171].

To address these problems, durable alternatives have been developed: non-phenolic resin-coated proppants remove toxic components and reduce groundwater pollution while optimising hardening kinetics to match fracture closure dynamics, thereby improving performance stability [172, 173]. Fly ash proppant, synthesised from coal-burning by-products, has enhanced compressive strength and durability.

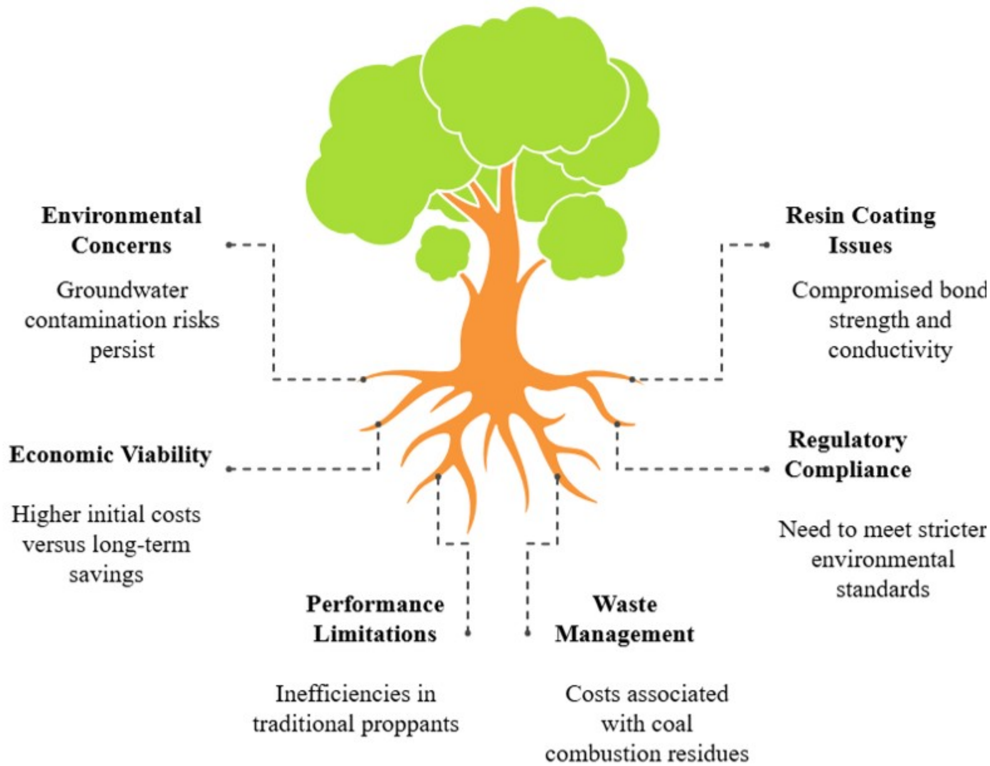

Figure 7. Transition Challenges in Low-Carbon Proppants Adoption

This approach reduces carbon emissions and helps recover industrial waste, aligning with the principles of the circular economy, as presented in Figure 8. Notwithstanding this advancement, propensity production continues to be linked to habitat disruption, soil erosion, and water pollution. Energy-intensive sintering processes, frequently reliant on fossil fuels, significantly impact the carbon footprint [174].

Mitigation options include microwave sintering, which expedites densification by volumetric heating, achieving up to 99% savings in hybrid systems. However, the challenges of scalability hinder widespread commercial adoption. Non-toxic coatings and low-temperature sintering minimise environmental impacts while maintaining mechanical integrity. Economically, low-carbon propellants can result in higher upfront costs, but they can achieve long-term savings through reduced ecological remediation, regulatory compliance and waste disposal expenditures [175, 176].

Fly ash propellers, for instance, diminish raw material expenses and coal waste disposal burdens while enhancing operating efficiency through improved heat resistance and crushing capabilities [177]. Biomass proppants originating from renewable sources provide an alternative sustainable solution. These biodegradable materials mitigate the effects of resource extraction, necessitate less production energy, and exhibit performance akin to traditional proppants [178].

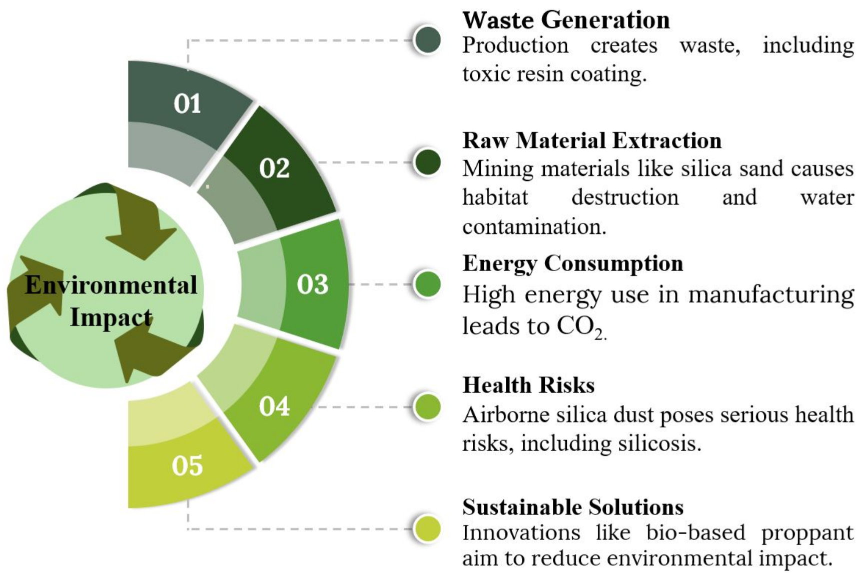

Figure 8. Environmental Impact and Solution in Proppants Production

Overall, the production of proppants faces considerable environmental barriers. However, progress in low-carbon materials (such as fly ash and bio-based raw materials), energy-saving processes (such as microwave sintering) and waste recovery offer viable solutions. This development aligns the decarbonisation objectives with the economic requirements of hydraulic fracturing operations [164].

Conclusion

The introduction of low-emission carbon reduction solutions derived from solid waste components signifies a fundamental shift in the hydraulic fracturing industry. This study examines the use of industrial by-products such as coal ash, coal gangue, and rice husk ash to enhance the material properties of proppants while significantly decreasing environmental impacts by reducing energy consumption and carbon emissions. Furthermore, the application of modern production methods, such as low-temperature sintering, illustrates the industry's robust commitment to sustainable practices consistent with the principles of a circular economy. Moreover, to use these advancements, the field must explore non-sintered support technologies crucial for attaining sustainable hydrocarbon extraction. The efficacy of these technologies relies on addressing technological, environmental, and regulatory challenges that currently impede their extensive dissemination. Future research should concentrate on the sustainability and scalability of non-sintering techniques, promoting interdisciplinary collaboration among engineers, environmental scientists, and policymakers. These targeted initiatives will facilitate transformative benefits, including reducing carbon emissions and improving resource efficiency, which will align hydraulic fracturing methods with the Sustainable Development Goals. With these sustainable options, the hydraulic fracturing industry can effectively address resource extraction issues while supporting environmental management and corporate responsibility. Ultimately, these collaborative efforts will ensure the resilience of the oil and gas sector in the future while maintaining low carbon emissions.

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