A Systematic Review of Ceramic Nozzle Manufacturing: Fabrication Methods, Strengths, Limitations, and Future Directions

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Abstrak, *Ceramic nozzles are used in a whole range of industrial applications, thanks to their excellent thermal, wear resistance, and durability in extreme environments. This study provides a Systematic Literature Review (SLR) leveraging PRISMA methodology evaluating methods, strengths, limitations, and future directions. This study groups together ceramic nozzle functions, production processes, strengths, and limitations to help determine the most productive fabrication approach. Findings reveal that conventional ceramic production methods allow for structural integrity, but modern additive manufacturing methods improve precision and scalability. Nevertheless, issues like brittleness and demanding manufacturing processes still pose major challenges. Emerging areas such as nano-ceramic composites, hybrid polymer, AI and machine learning-driven manufacturing, and sustainable sintering techniques can establish a new paradigm for performance and cost-effectiveness in future research. Moreover, pursuing biomedical and energy system applications would be another area of potential for ceramics material versatility and industrial applications like spray coating and coal slurry boiler.*
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Keywords *: Ceramic, Nozzle, Manufacturing, Methods, Direction*

1. Introduction

In industrial applications, ceramic nozzles are essential components, known for their excellent heat and wear resistance, chemical stability, and ability to withstand elevated temperatures and aggressive media. One of those materials is ceramics, which show performance in extreme conditions without oxidation [1]. These materials exhibit excellent erosion and thermal shock resistance, finding applications in aerospace, energy, and fluid-dynamics, among others [2][3]. In addition, the mechanical strength of ceramic microstructures can be tailored by decreasing porosity and grain-size reduction [4].

Hand building, slip casting, extrusion, and pressing are of traditional ceramic manufacturing. Hand building also offers much flexibility in design and provides scope all around for creating unique and complex ceramic forms [5]. The use of slip casting technique in combination with pressureless sintering leads to homogenous microstructures with an even distribution of grain sizes while minimizing defects like micropores and agglomerates [6]. The control over anisotropic powder to direct magnetically responsive particles during slip casting [7]. The high level of fiber alignment in the ceramic structures achieved due to the extrusion process improves mechanical properties [8]. Moreover, hot pressing is capable of achieving high densifications with fine crystal size that enhances the strength and toughness of the material [9].

Recent advancements in ceramic manufacturing include emerging modern techniques such as injection molding and 3D printing. These techniques provide higher accuracy, lower material waste, and the ability to build complex shapes with exceptional dimensional precision. Having good surface quality with low shrinkage and high compressive strength [10]. Therefore, integrating conventional methods with additive manufacturing has shown a promising pathway to achieving excellent mechanical properties in terms of strength and reduced density of ceramics enabling its mass production on super industrial scale [11][12].

Despite ongoing research in ceramic nozzle manufacturing, significant gaps remain. In recent years, 3D printing has gained more attention in relation to the integration of artificial intelligence (AI) in the field of ceramics [13]. Another field of study is the 3D printing of multi-material nozzles, which also enables the production of a functionally graded material with desired properties [14]. Nevertheless, despite the benefit in the mechanical performance of ceramic nozzles, there is still room for improvement in their performance

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in extreme environments, such as those in water processing and air processing systems [15][16]. High thermal, chemical, and mechanical resistance and low density sustain the interest of aerospace engineering in advanced ceramics [17]. Recent technology has revealed an energy-efficient one-step laser pyrolysis method for synthesizing high-purity HfC with promising additive manufacturing applications. However, its practical implementation is limited by oxidation issues and the need for further process optimization [18] Moreover, ceramic thermal, mechanical, and electronic data must be standardized for industry user needs. This needs collaboration from everyone to design and compare public datasets of improvement on the performance of ceramic nozzles [19].

In contrast, most studies to date have evaluated individual manufacturing techniques rather than offering an overview and comparison of ceramic nozzle production methods. This study aims to fill this void through systematic evaluations of the pressing and manufacturing methods to identify the optimal approach to high-performance ceramic nozzle production. It furthermore possesses the benefits, limitations, and future directions for working ceramic nozzles. The results of this study will be a reference for designing ceramic nozzle manufacturing for material science and engineering in the industry.

2. Method

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure a structured and transparent approach in conducting the Systematic Literature Review (SLR). The PRISMA framework is shown in Figure 1 and applied as follows:

2.1. Identification

Structured searches by Publish or Perish software were conducted in academic databases from Scopus between the years 2010 and 2025 with the title words include "ceramic nozzle ". A total of studies were retrieved initially before screening.

2.2. Screening

Duplicate studies were removed. Studies that did not meet the inclusion criteria (e.g., non-English papers, irrelevant focus, lack of empirical data, review paper) were excluded.

2.3. Eligibility

Full-text assessment was conducted on the remaining studies. Inclusion criteria studies must focus on ceramic nozzle manufacturing using at least one of the six evaluated techniques be published in peer-reviewed journals between 2010 and 2025, and include performance evaluations. Exclusion criteria studies act on insufficient methodological details or performance comparisons.

2.4. Data Extraction and Analysis

Extracted data include function, manufacturing process, strength, and limitations. Comparative analysis was conducted to identify the trends, strengths, and limitations of each method. This analysis then synthesized to generate future direction for creating advanced ceramic nozzles.

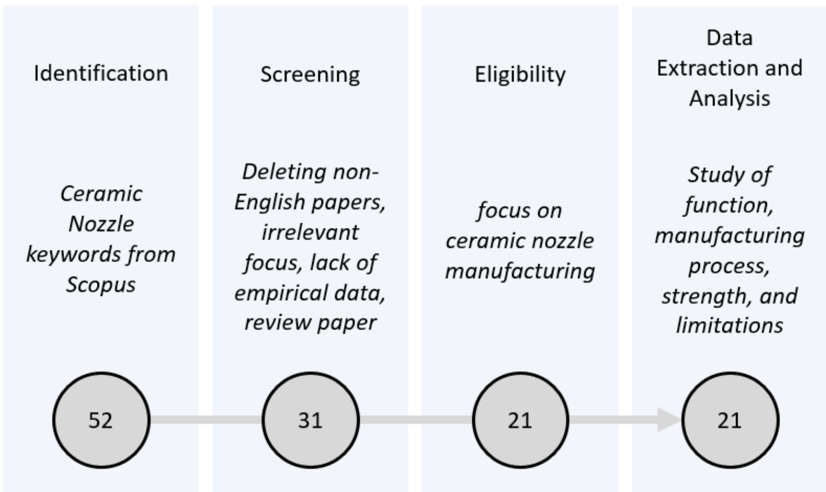

Figure 1. Schematic of the Review Process

3. Result and Discussion

3.1. Systematic Literature Review Result

The search was executed with the keyword "ceramic nozzle" in the Publish or Perish search engine, with a publication year range from 2010 to 2025 and below the scope of Scopus journal, a total of 52 papers were obtained at the beginning. The abstracts of papers were screened by various criteria: limiting to published papers written in English, relevance to the research question, availability of empirical data, and exclusion of review papers. Following this filtering procedure, 21 papers were rejected and 31 papers remained.

Data was further refined to examine ceramic nozzle manufacturing techniques and followed by performance reviews. Five papers were excluded for not being peer-reviewed, while five others were excluded due to irrelevant results, leading to a total of 10 papers. We extracted specific data from these selected papers and classified them into four groups: nozzle function, manufacturing function, strength, and limitations. Table 5 shows the global results of the review process for the identified topics. This study delves into and summarizes all the characteristics, applied methods, and performance results for future ceramic nozzle production, where aspects of various techniques are analyzed and compared to provide insights into the most suitable approaches for ceramic nozzle manufacturing.

3.2. Function of Nozzle

From the overall results, the initial data analysis focuses on identifying the primary applications and functions, as presented in Table 1.

Table 1. Application and Function of Nozzle Manufacturing Process

No	Reference	Specialized Application	Function of Nozzle
1	J. Deng [20]	Industrial coal-water slurry boilers	Erosion wear resistance
2	Y. Feng [21]	Abrasive spraying systems	Wear resistance
3	S. Junlong [22]	Abrasive air-jet systems	Erosion resistance
4	D. Jianxin [23]	coal-water slurry systems	Wear resistance
5	J. Deng [24]	Industrial applications	Enhanced durability
6	X. Tian [25]	Engineering ceramics machining	Micro-detonation
7	S. Afazov [26]	Droplet scanning systems	Micro-drilling precision
8	R. Zheng [27]	Ramjet propulsion systems	High-performance propulsion
9	K. Beyerlein [28]	Serial femtosecond crystallography	Micro-injection delivery for crystallography
10	S. Junlong [29]	Industrial equipment	Impact resistance
11	B. Sayinci [30]	Agricultural spraying systems	Optimized flow for spraying
12	V. Piotter [31]	X-ray free-electron laser systems	Liquid jet nozzles
13	H. Li [32]	Industrial applications	High-temperature micro-nozzles for precision applications
14	R. Thirunavukkarasu [33]	Diesel engine fuel injectors	Fuel injection efficiency
15	M.P. Massola [34]	Spray optimization	Spray distribution optimization
16	K.S. Kim [35]	Rocket propulsion	High-temperature resistance
17	Y. Zhu [36]	Hybrid rocket propulsion	Hybrid rocket nozzle with advanced composites
18	S. Mungiguerra [2]	Rocket technology	High-temperature resistance and durability
19	B.S. Karpinos [37]	Turbine vanes	Thermal stress resistance in nozzle vanes
20	E. Schwarzer-Fischer [17]	Space applications	Precision manufacturing
21	D. Sciti [3]	Rocket propulsion testing	Ultra-high-temperature applications

The classified items fall into five main application categories, which include industrial and energy applications, scientific and precision applications, agricultural and chemical spraying systems, fuel injection and combustion systems, and aerospace and rocket propulsion applications. The distribution between these categories is shown in Figure 2. Industrial and energy nozzles include ceramic nozzles in coal-water slurry boilers, which are also used in abrasive air-jet and machining applications, where erosion and wearability are critical to operating life. High-precision nozzles such as those used for X-ray-free-electron lasers, crystallographer sample delivery, and micro-injection systems in scientific and precision applications, where precision, stability, and mono dispersion control are keys. Agriculture-chemical and mine spray systems are characterized by the droplet rate and its distribution to optimize fluid application in agriculture or industrial chemical applications to improve the yield and reduce waste. They also involve ceramic nozzles made specifically for diesel engine purposes along with various internal combustion applications, which provide more efficient spray patterns, fuel atomization, and optimize combustion processes. Finally, aerospace and rocket propulsion applications include high-temperature-resistant nozzles for ramjet systems, hybrid rockets, and extreme propulsion testing, where thermal stability and mechanical integrity are critical for operational success in extreme environments. These classifications reflect the diverse applicability of a ceramic nozzle to various industries, emphasizing their crucial function of improving performance, efficiency, and longevity under challenging operational circumstances.

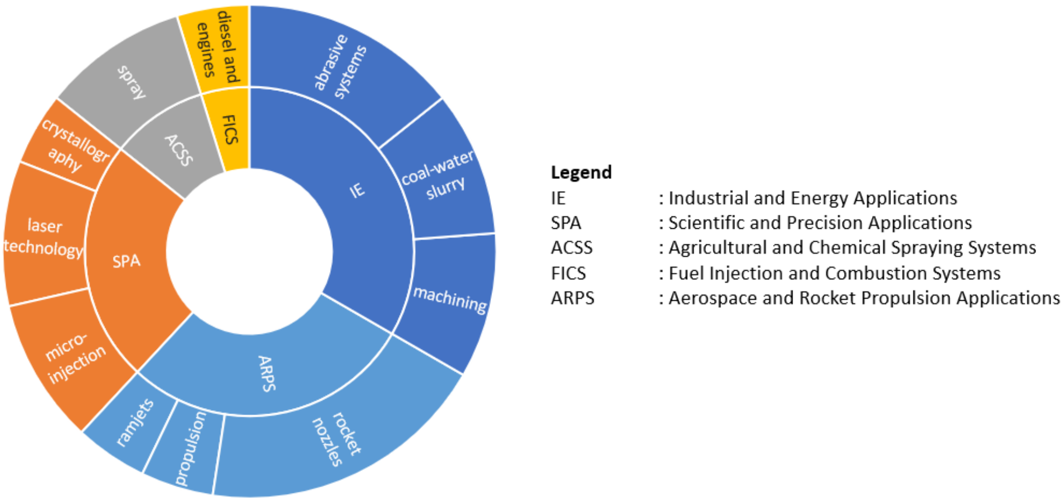

Figure 2. Application Category of Ceramic Nozzle

Ceramic nozzles are used in various industries to cope with extreme conditions related to erosion and high abrasion [20], [21]. In high-pressure air-jet and coal-water slurry systems, homogenous abrasive particles bombard a surface, and ceramic materials are highly resistant to this type of wear [22], [23]. Conventional metals have high hardness, but they wear out quickly when used with abrasive particles [24]. Furthermore, the erosion resistance of ceramic composites can be improved further with reinforcement leading to its adoption in the manufacturing and energy sectors [20], [23].

In the case of nozzles for rocket propulsion and jet engines, [35], [36] where one while working at a high temperature must have a high material strength as compared to the thermal stress generated. Advanced ceramics (e.g., silicon carbide (SiC) and hafnium carbide (HfC)) are used to enhance performance in high-temperature applications, such as rocket propulsion systems and gas turbines [2],[3]. One of the main advantages of these materials is their capacity to withstand very high temperatures, over 2000 °C [27]. Lastly, in order to improve resistance to thermal shock, increase nozzle life, and minimize the possibility of structural failure, composite-based nozzles are currently under development [17], [37].

For instance, jet engines such as ramjet engines and fuel injection systems utilize nozzles that regulate gas and fuel flow to achieve the best performance [27], [35]. The control mechanism is more stable, allowing for increased fueling efficiency and reduced emissions due to better fuel control by exposing nozzle geometry and heat-resistant materials [29], [33]. Another example is the application of ceramic-based fuel injectors on diesel engines which showed enhanced spray efficiency, thus improving combustion performance [30]. However, it has been found out that nozzles made from metal are not as good at withstanding high pressure and temperature as those made from ceramic composite [2], [3].

Nozzles play an important role in spraying systems across a range of industries including agriculture, manufacturing, and chemical processing [30], [34]. The spray efficiency of ceramic nozzles can be optimized by the desired flow characteristics, better droplet distribution, reduced liquid usage, decreased drift, and better application quality [28], [31]. Both the nuclear magnetic resonance

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magnetic field [14,16] and the X-ray free-electron laser field [17] also use ceramic liquid nozzles to generate precision liquid jets for scientific experiments in these fields. Micro-injection ceramic-based spraying systems are also used for high-precision control for applications in the pharmaceutical and electronics industries [24], [26].

In addition, production technologies are advancing rapidly, further supporting the application of ceramics for nozzle manufacturing [2],[31]. Specific nozzle geometries with high complexity and precision have been achieved using methods like ceramic photopolymerization-based manufacturing [17]. These technologies enable the manufacture of symmetrical microstructured nozzles, increasing their durability while reducing material wastage. To improve efficiency and accuracy, ceramic processing methods such as micro-EDM are also employed [32].

3.3. Manufacturing Process

The second analysis focuses on categorizing the manufacturing processes. As shown in Table 5, these processes can be classified into five groups, which are presented in Table 2. This classification provides valuable insight into the overall production of ceramic nozzles and helps guide future research directions.

Table 2. Grouping of Nozzle Manufacturing Process

No	Manufacturing Process Group	Specific Manufacturing Process
1	Traditional Ceramic Processing Methods	• Laminated ceramic • Sintered ceramic • Ceramic matrix composite processing • Ceramic Matrix Composites (CMC) processing
2	Advanced Ceramic Processing and Fabrication cell	• Layered ceramic structures • Gradient ceramic fabrication • HfC-SiC Composite Fabrication • Max Phase Ceramic Processing • High-temperature composite processing • Advanced composite bonding C/SiC Composite Manufacturing
3	Machining and Material Removal Processes	• Micro-detonation machining • Micro-drilling • Micro-EDM segmented milling • Abrasive air-jet processing
4	Molding and Coating Techniques	• Micro-injection molding • Injection molding • Ceramic coating • Lithography-based photopolymerization
5	Spray and Flow Optimization	• Strainer optimization in spraying • Spray pattern optimization

The conventional methods of processing ceramics are fundamental to producing robust and high-performance ceramic nozzles. For example, laminated ceramics, sintering, and ceramic matrix composite (CMC) processing [20], [23] can manufacture dense and structural ceramic components. Improving the densification and refining the crystal size can guarantee that ceramic keeps robust mechanical and microstructure properties, as demonstrated by a few research using these techniques [9].

We have recently made progress in ceramic processing, as examples of layered ceramic structures, gradient ceramic fabrication, and high-temperature composite processing have been developed. These techniques improve the structural strength and performance characteristics of ceramic nozzles by refining the grain structures and enhancing the porosity [20], [24]. Such progress in both carbides qualifies composite manufacturing, such as C/SiC and HfC-SiC composites, which have a notable impact on the thermal resistance and mechanical properties due to a significant increase in ceramic nozzles and its applicability to propulsive devices in the aerospace [2],[27], [35].

Ceramic nozzles require intricate designs that can be achieved through precise machining techniques. Micro-detonation machining, micro-drilling, micro-EDM segmented milling, and abrasive air-jet processing provide precise material removal suitable for complex geometries and smooth inner surfaces [22], [25], [26], [32]. These machining processes improve the functionality of nozzles by ensuring a stable fluid passage while minimizing turbulence. In another study, the average droplet sizes decreased significantly, but went to very high velocities, possibly at very high injection pressures. Furthermore, increasing injection pressures resulted in larger integral length scales of the turbulence and higher air entrainment into the spray than that found at lower injection pressures [38].

Advanced manufacturing methods, precisely injection molding, micro-injection molding, and lithography-based photopolymerization, enable large-scale production of piezoelectric ceramic nozzles with complex and highly controllable geometrical features [17], [31]. These techniques allow for the production of lightweight and robust ceramic parts with close tolerances [28]. Thermal and chemical protection is also achieved by ceramic coating processes, which generally improve the nozzle surface properties to provide more wear and corrosion resistance. It is a significant advantage in harsh chemical and high-temperature environments [33], [37].

Determining the best internal configurations and benefits of ceramic nozzles is of interest as every industrial application needs to achieve the best efficiency. Fluid dynamics and jet optimization integrate processes including strainer optimization in spraying [30] and spray patterns [34] to assure uniform droplet distribution and controlled fluid dynamics. This former improves the performance of ceramic nozzles in applications, including agricultural spraying [30], industrial cooler, and fuel injection [33], where accuracy and efficiency are crucial for operational effectiveness.

3.4. Strength and Limitation

The third analysis focuses on categorizing the strengths and limitations, as outlined in Table 3 and Table 4.

Table 3. Grouping of Ceramic Nozzle Strength

No	Strength	Specific Advantages
1	Wear and Erosion Resistance	• High erosion resistance • Superior wear properties • Enhanced lifespan under abrasion • Optimized durability for coal-water slurry • Improved impact resistance
2	Structural and Mechanical Strength	• Enhanced structural integrity • Better structural integrity under stress • Enhanced hybrid material bonding • Improved micro-structure and heat resistance • High endurance under extreme heat
3	Thermal and High-Temperature Performance	• High-temperature and durability properties • Superior thermal stability • Extreme temperature resistance
4	Precision and Performance Enhancement	• Precision machining • High precision and batch reproducibility • Enhanced surface quality
5	Flow, Spray, and Efficiency Optimization	• Improved droplet system performance • Optimized droplet velocity and distribution • Fuel efficiency improvements • Better spray control • Mass production capabilities

Ceramic nozzles are known for their high resistance to wear and erosion, making them suitable for applications in abrasive environments. Because of their high erosion resistance and excellent wear properties, they exhibit resistance to long-term use at aggressive conditions, for example in coal-water slurry systems [20] applications and industrial spraying applications [30]. The long life under abrasion translates into comparatively less upkeep cost and higher operating efficiency [21]. On top of this, as ceramic nozzles are much more wear-resistant than metal-based nozzles, they can lower the amount of material degradation, which makes them an ideal material in areas where mechanical wear is an issue [22].

Another advantage ceramic nozzles have is their structural integrity withstanding heavy operational stresses, leading to durability in the long run. The unique structure of the material enables it to hold ventilation open even at high-pressure [20]. Moreover, improvements in the micro-structure and heat resistance of ceramic nozzles also led to significantly better performance and durability in high-temperature application [35]. Therefore, ceramic nozzles are proven to be a good choice in applications that are intended to endure and deform minimally, as they also exhibit strong mechanical properties [36].

Due to outstanding thermal stability, ceramic materials are perfect candidates for usage in aerospace propulsion and other high-temperature industrial processing applications [35]. The main advantage of ceramic nozzles is their resistance to extreme temperatures without compromising structural integrity, compared to traditional metallic nozzles [3]. As they offer better thermal stability and durability, ceramic nozzles can be used effectively in harsh conditions, like rocket propulsion systems and industrial burners [2]. The blemish-free surface exhibits extreme temperature resistance that guarantees high-performance capabilities up to most extreme thermal regimes [37].

Ceramic nozzles also have a critical advantage in precision machining, enabling high accuracy and tight tolerances for components [32]. They can deliver high accuracy and batch reproducibility, providing consistent performance across multiple applications [31]. Additionally, improved surface quality in ceramic nozzles reduces friction and wear thereby improving their overall efficiency [26]. The precise control of ceramic nozzle manufacturing enables their use in highly-specialized areas like laser cutting, medical devices, and aerospace propulsion, where accuracy and reliability are essential [28].

Table 4. Grouping of Ceramic Nozzle Weaknesscess

No	Limitations	Specific Limitations
1	Manufacturing and Processing Challenges	• Complex manufacturing process • Requires specialized processing • Requires advanced fabrication techniques • Requires specialized EDM techniques • Requires extreme processing conditions • Requires specialized equipment
2	Cost and Scalability Issues	• Material cost and processing complexity • High production costs • Expensive production equipment • Difficult to mass-produce • Limited to small-scale applications
3	Mechanical and Structural Limitations	• Brittle under high stress • Sensitive to impact angles • Difficult material bonding • Limited material options • Limited compatibility with engine materials
4	Performance and Operational Constraints	• Requires advanced ignition control • Challenging drilling conditions • Complex spray optimization • Subject to clogging and flow inconsistencies
5	Environmental and Durability Concerns	• High-temperature degradation risk

Ceramic nozzles are important in directing fluid and gas flow in spray and fuel injection systems [30]. The ability to optimize not only droplet velocity distribution but also the droplet system itself leads to the improvement of spraying efficiency, avoiding droplet losses and improving spraying coverage reducing the material waste [34]. The application of ceramic nozzles allows more accuracy in the atomization of fuel and, therefore, contributes to fuel economy improvements [33]. This superior spray control ability can be valuable in agricultural, automotive, and industrial applications where uniform fluid coverage is critical to system performance [30]. Furthermore, their potential to enable mass production capabilities offers scalability for large-scale industrial applications [31].

Besides all the benefits ceramic nozzles have also some drawbacks. Being produced using complex manufacturing techniques, their production requires high accuracy and special processing methods. Highly skilled labor and sophisticated machinery are imperative for advanced fabrication processes like micro-EDM and ceramic matrix composite processing [32]. Moreover, the high-temperature and pressure environment required for sintering and shaping ceramic materials increases the production challenges. Achieving this required level of structural integrity typically requires specialized equipment, which adds even more complexity and cost to manufacturing [17].

This fact makes procurement of engineered ceramic products relatively costly and labor intensive. In contrast to metal nozzles that are produced more effectively utilizing conventional methods, ceramics are made with costly materials and in energy-expensive [17]. fabrication methods. These problems make mass production a challenge, restricting ceramic nozzles to niche or small-scale implementations [32]. Additionally, the expensive nature of selecting ceramic nozzles limits the budget for the industries.

Although ceramic nozzles have excellent thermal and wear resistance, they have mechanical limitations. At high-stress applications, the glass is brittle and can crack or break with sudden impact [21]. Since it has a few options for the materials from which to select, it can hardly be adapted to work in various applications, and some ceramic compositions may be incompatible with some parts in the engine [29]. Poor bonding of the material can also worsen its durability and necessitate the use of advanced techniques to improve the interlaminar adhesion among composite layers [36].

Ceramic nozzles used in high-performance applications, like aerospace propulsion and fuel injection, must operate under stringent performance requirements. This situation can be difficult to analyze and to control droplet distribution and achieve satisfactory coverage of agricultural structures, which requires acceptable spray optimization [30]. Moreover, ceramic nozzles are often vulnerable to impact angles that influence their efficiency in erosive surroundings [29]. Further operational challenges like clogging and flow irregularity also beget demanding engineering considerations to ensure stable nozzle delivery for the duration of its use [30], [34].

Ceramic nozzles are the best option when operating in a high-temperature environment, but these materials are not immune to high-temperature degradation when exposed to high temperatures for an extended period [35]. Similarly, if you read the entire sentence towards the end of a probable drop statement, you could end up using them. They are also better suited for applications where durability is required under radian thermal conditions, but not sustained [37]. To surmount this problem, novel research efforts are now being concentrated on the development of composite ceramic materials with improved resistance to thermal stresses and environmental degradation.

Comparative recommendation scores can be generated from strengths and weaknesses for ceramic nozzle manufacturing methods, it is shown from figure 3.

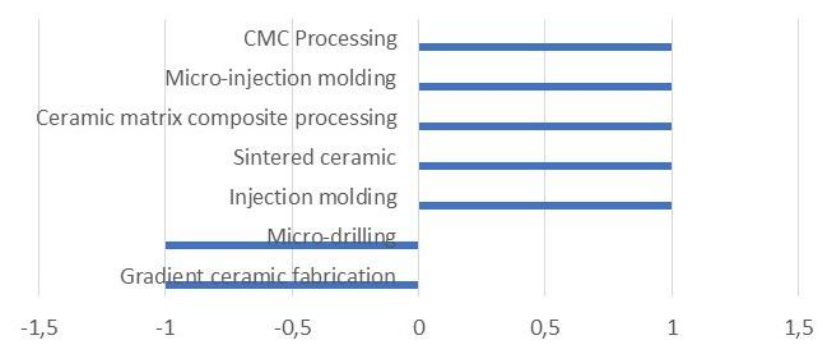

Figure 3. Ranking of Ceramic Nozzle Manufacturing Techniques by Performance Score

Techniques like C/SiC composite manufacturing and injection molding rank highest due to their superior performance and scalability for industrial applications. In contrast, methods such as abrasive air-jet processing and micro-detonation machining are less favorable due to high complexity and limited adaptability. This visualization helps prioritize manufacturing techniques that balance high performance with practical feasibility.

3.5. Future Direction

While this study has conducted a comprehensive review of ceramic nozzle manufacturing methods, emphasizing their strengths and limitations, several areas still necessitate further research and development. Future research directions are illustrated in Figure 4. Material enhancement is one of the main issues as the existing ceramic nozzles are heat resistant but they demonstrate brittleness and compatibility issues. Nano-ceramic composites and hybrid ceramic-polymer structures to improve the durability of bonding properties while maintaining thermal stability should be the focus of future

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studies. Another challenge is fabricating ceramic nozzles, where the cost of manufacturing remains high, and can limit the cost-effective and scalable production of these components. Investigations on sustainable and energy-optimized sintering methods should be carried out to enable large-scale industrial use of ceramic nozzles.

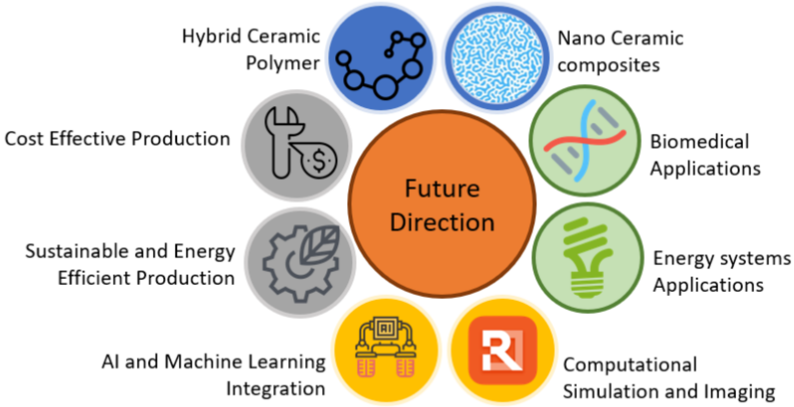

Figure 4. Future Research Directions in Ceramic Nozzle Development

Opportunities for progress also arise from advancements in manufacturing technology. By incorporating process optimization with AI and defect detection with machine learning, this could lead to a substantial increase in accuracy and productivity. In the future, further studies should focus on technologies such as real-time monitoring systems/tools in association with ceramic fabrication to optimize quality control to limit defects in ceramic components. Experimental and numerical techniques such as CFD simulations and also high-speed imaging could provide a more detailed understanding of spray dynamics, turbulence management, and the efficiency of fuel atomization. Advanced nozzle performance can be utilized with data approaches to optimize operational efficiency across applications.

Another promising research direction is to expand the industrial application of ceramic nozzles. Although they are widely used in aerospace and fuel injection systems, their capability in biomedical applications, hydrogen energy systems, and precision microfluidics are not yet fully explored. The work is pulling in new directions with exciting prospects and establishing its relevance in key industries of chemical reactors and medical fluid delivery systems of ceramic nozzles which will someday become a game-changer from an industrial point of view and new technological advancements to be seen in the future. The generation of ceramic nozzles will support their widespread use in multiple high-technology sectors.

4. Conclusion

Thus, this study systematically reviewed the noise manufacturing processes of ceramics functional applications as well as their strengths and limitations. Nonetheless, numerous successful applications in the industry face hurdles that limit the use of ceramic nozzles due to high production costs, brittleness, and limitations of materials.

Finally, future studies should work on improving material composites like nano-ceramic composites and hybrid ceramic-polymer structures to achieve durability and adaptability. Nozzle performance, efficiency, and lifespan can also see significant advancements through AI-driven process optimization, CFD analysis, and high-speed imaging. To achieve more efficient and scalable industrial production, future ceramic nozzle manufacturing should prioritize the integration of hybrid additive techniques with AI-assisted process optimization and sustainable sintering, enabling mass fabrication of high-performance nozzles with reduced cost and enhanced durability.

In addition, broadening the utilization of ceramic nozzles from aerospace and fuel injection to biomedical, microfluidics, and renewable energy sectors presents valuable avenues for further study. Overcoming these material, and techno-economic challenges will open the door to next-generation ceramic nozzles with enhanced performance, cost, and industrial scalability.

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Table 5. Overall results of the review process for the identifed topics

Reference	Manufacturing Process	Strength	Limitation
J. Deng [20]	Laminated ceramic	High erosion resistance	Complex manufacturing process
Y. Feng [21]	Sintered ceramic	Superior wear properties	Brittle under high stress
S. Junlong [22]	Abrasive air-jet processing	Enhanced lifespan under abrasion	Material cost and processing complexity
D. Jianxin [23]	Layered ceramic structures	Optimized durability for coal-water slurry	Requires specialized processing
J. Deng [24]	Gradient ceramic fabrication	Enhanced structural integrity	Difficult to mass-produce
X. Tian [25]	Micro-detonation machining	Precision machining	Requires advanced ignition control
S. Afazov [26]	Micro-drilling	Improved droplet system performance	Challenging drilling conditions
R. Zheng [27]	C/SiC Composite Manufacturing	High-temperature and durability properties	High production costs
K. Beyerlein [28]	Micro-injection molding	Mass production capabilities	Limited to small-scale applications
S. Junlong [29]	Ceramic matrix composite processing	Improved impact resistance	Sensitive to impact angles
B. Sayinci [30]	Strainer optimization in spraying	Optimized droplet velocity and distribution	Subject to clogging and flow inconsistencies
V. Piotter [31]	Injection molding	High precision and batch reproducibility	Expensive production equipment
H. Li [32]	Micro-EDM segmented milling	Improved micro-structure and heat resistance	Requires specialized EDM techniques
R. Thirunavukkarasu [33]	Ceramic coating	Fuel efficiency improvements	Limited compatibility with engine materials
M.P. Massola [34]	Spray pattern optimization	Better spray control	Complex spray optimization
K.S. Kim [35]	HfC-SiC Composite Fabrication	Superior thermal stability	Requires extreme processing conditions
Y. Zhu [36]	Advanced composite bonding	Enhanced hybrid material bonding	Difficult material bonding
S. Mungiguerra [2]	High-temperature composite processing	High endurance under extreme heat	Requires specialized equipment
B.S. Karpinos [37]	Max Phase Ceramic Processing	Better structural integrity under stress	High-temperature degradation risk
E. Schwarzer-Fischer [17]	Lithography-based photopolymerization	Enhanced surface quality	Limited material options
D. Sciti [3]	Ceramic Matrix Composites (CMC) processing	Extreme temperature resistance	Requires advanced fabrication techniques