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Original Article

Bio-Nanocoolants in Electropolishing: Corrosion Behavior, Prospects, and Potential Applications

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Abstract - *The integration of bio-based nanofluids as coolants in the electropolishing process offers a promising pathway for industrial diversification. These nanofluids not only enhance surface quality but also contribute to sustainable manufacturing. Electropolishing, an electrochemical process that naturally generates heat, requires careful thermal control to avoid localized overheating and maintain stable operation in advanced manufacturing settings. This work examined bio-nanocoolants prepared from biodegradable base fluids combined with nanoparticles such as* Al_2O_3*,* CuO*, and* TiO_2*. The tests showed that adding these nanoparticles increased thermal conductivity by as much as 18% and lowered the surface roughness of stainless steel after electropolishing by about 25% compared with traditional electrolytes. Some of the nanoparticles also acted in a catalytic manner, improving the efficiency of anodic dissolution. Importantly, the bio-nanocoolants proved to be non-corrosive and met environmental requirements. Overall, the study suggests that bio-nanocoolants not only enhance electropolishing performance but also support the broader goals of sustainable and environmentally responsible manufacturing.*

Keywords *- Bio-nanocoolant, Electropolish, Stainless steel.*

1. Introduction

Electropolishing is an electrochemical finishing method commonly used to improve the surface quality of metals by selectively dissolving material from their outer layer. It is especially valued for producing bright, smooth, and corrosion-resistant surfaces, which makes it widely applied in aerospace, medical devices, electronics, and food processing industries [1-3]. Despite its advantages, the technique generates considerable heat because of the current passing through the electrolyte and the exothermic nature of the reactions. Rising temperatures introduce a number of difficulties: excessive heat may cause non-uniform material removal, hot spots on the workpiece, poorer surface finish, or even deterioration of the electrolyte itself [4, 5].

Elevated temperatures can also accelerate unwanted reactions, raise energy demands, and reduce the dimensional precision of finished parts. For these reasons, managing heat effectively is essential to maintain both process reliability and product quality. Conventional cooling approaches often rely on synthetic coolants or external chilling units to stabilize the electrolyte temperature [6, 7]. Although such systems work, they usually depend on petroleum-based or chemically intensive fluids. These materials are not always biodegradable, may be hazardous, and are often difficult to dispose of responsibly.

This creates a conflict with current efforts toward greener and safer manufacturing. To overcome these shortcomings, researchers have turned to more sustainable alternatives. One promising approach is the use of bio-nanocoolants-cooling media derived from renewable bio-based liquids and improved with nanoparticles to enhance thermal and functional behavior. Interest in this area has grown quickly, with the number of related studies reported in Google Scholar increasing substantially in recent decades. Between 1990 and 2000, approximately 300 papers were published, marking the early exploratory phase, as can be seen in Figure 1 illustrates the growth of research publications on bio-nanocoolants from 1990 to 2025.

This number rose to around 2,000 publications from 2000 to 2010, reflecting an initial expansion of interest. A substantial surge occurred in the 2010–2020 period, with about 9,000 papers published-an increase of more than fourfold over the previous decade, driven by advances in nanotechnology and rising demand for sustainable cooling solutions. The trend continued to climb sharply between 2020 and 2025, during which 12,000 papers were published-a further 30% increase within just five years. This sharp growth highlights the increasing importance and application of bio-nanocoolants in thermal management, surface processing, and environmentally conscious manufacturing (Google Scholar, accessed 2025).

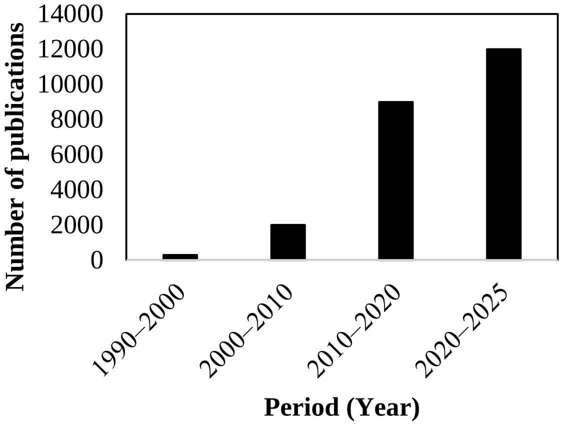

Fig. 1 The growth of research publications on bio-nanocoolants from 1990 to 2025. The data highlights significant increases in publication numbers, especially from 2010 onward

Publication data specifically on bio-nanocoolants for electropolishing remain limited, highlighting a significant research gap. A focused search on *Google Scholar* using the keywords "bio-nanocoolants + electropolishing" yields only 336 publications between 1990 and 2025. This modest figure contrasts sharply with the exponential growth in broader nanofluid research, indicating that the application of bio-nanocoolants in electropolishing is still a niche and underexplored area. Meanwhile, parallel advancements in green electropolishing—such as the use of deep eutectic solvents and ionic liquids like choline chloride—demonstrate increasing interest in sustainable surface treatment technologies. Despite the limited number of direct studies, the convergence of green chemistry, nanotechnology, and precision surface finishing suggests substantial potential for future research and industrial application in this emerging field.

1.1. From Nanofluids to Bio-Nanocoolants: A Technological Evolution

The progress of bio-nanocoolant technology can be traced through several stages. Before the 1990s, thermal management systems generally depended on basic fluids such as water, ethylene glycol, or mineral oils. While these coolants were widely available and functional, they offered limited thermal efficiency and raised concerns about long-term sustainability. In the 1990s, researchers began to experiment with nanofluids by dispersing metal-oxide particles, including Al_2O_3 and CuO, into synthetic liquids. This period marked the first attempt to exploit nanoscale additives for better heat transfer. Interest in this approach expanded between 2000 and 2010, when more studies verified that nanoparticles could significantly improve conductivity and overall cooling performance. By the following decade, environmental considerations gained momentum, encouraging the use of renewable bases such as vegetable oils, glycerin, and bio-ethanol. Combining these greener fluids with nanoparticles gave rise to what is now recognized as bio-nanocoolants—engineered fluids that balance thermal efficiency with eco-friendly design. The period from 2020 to 2025 witnessed rapid growth in this field, with over 12,000 papers published according to Google Scholar. Research in this phase focused on advanced applications, such as using TiO_2 and ZnO nanoparticles in bio-based fluids for electropolishing, food packaging, and energy systems.

Overall, bio-nanocoolants have progressed from basic cooling agents to multifunctional, sustainable materials aligned with green engineering principles. Table 1 is a visual timeline showing the historical development of bio-nanocoolant research, from the use of conventional coolants to modern bio-based nanocomposite innovations. Let me know if you would like this saved as an image or added to a document.

Table 1. Evolution of bio-nanocoolant research

Year Range	Development Stage
Pre-1990	Use of conventional coolants (water, ethylene glycol) dominates
1990–2000	Early research on nanofluids begins with metal oxide nanoparticles.
2000–2010	Nanofluid technology gains momentum, enhancing thermal properties.
2010–2015	Exploration of bio-based fluids (vegetable oils, glycerin)
2015–2020	Integration of nanoparticles into biofluids; the bio-nanocoolant term is introduced
2020–2025	Rapid development and application of green technologies and industrial processes

2. Principles of the Electropolishing Process

Electropolishing is an electrochemical process designed to remove a thin layer of material from a metallic workpiece, resulting in a smoother, cleaner, and more corrosion-resistant surface. It is essentially the reverse of electroplating and involves the controlled anodic dissolution of metal in an electrolyte solution under specific electrical and chemical conditions. At its core, the electropolishing process is governed by Faraday's laws of electrolysis [8].

The metal part to be polished is made of anode (positively charged), while chemically inert or corrosion-resistant material—usually stainless steel—is used as the cathode (negatively charged). When a Direct Current (DC) is applied across the electrodes immersed in the electrolyte, metal ions from the surface of the anode dissolve into the solution. Figure 2 illustrates a schematic of the electropolishing process, which transforms a rough metal surface into a smooth and uniform finish by selectively dissolving microscopic surface peaks. This is achieved through an electrochemical reaction where the workpiece acts as the anode and is connected to a power supply along with a cathode, both immersed in an electrolyte solution [9].

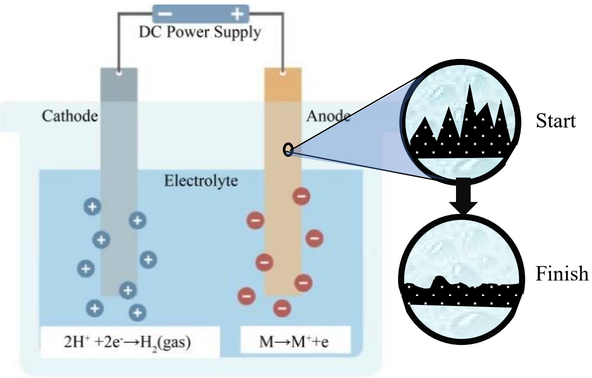

Fig. 2 (a) A schematic of the electropolishing process, and (b)Transformation of the metal surface from rough to smooth.

The amount of metal dissolved during the electrochemical process follows Faraday's law, and is influenced by the metal's density, the amount of current applied, and the duration of the process (Equation 1). The formula that describes the amount of metal dissolved or deposited during an electrochemical process is [9]:

$$m = \frac{Mit}{nF} \tag{1}$$

Where: m = mass of metal dissolved or deposited (in grams), M = molar mass of the metal (g/mol), I = current (in amperes, A), t = time (in seconds, s)

The key to achieving a smooth surface lies in the preferential removal of microscopic high points—or "*peaks*"—on the metal surface [10, 11]. These protrusions experience a higher current density compared to recessed areas, which leads to faster material removal at the peaks. Over time, this effect gradually levels the surface, reducing roughness and enhancing reflectivity. Several critical parameters influence the electropolishing process, including electrolyte composition, current density, voltage, temperature, and polishing time. The electrolyte is typically a highly viscous, acidic solution—commonly a mixture of phosphoric and sulfuric acids—that must be both conductive and effective at dissolving metal ions. Current density must be maintained within an optimal range to ensure uniform material removal; if too low, polishing is ineffective, while excessively high levels can cause surface defects such as pitting or burning. Voltage and temperature must also be carefully controlled to preserve electrolyte activity and prevent undesirable electrochemical reactions. Additionally, polishing time must be tailored to the specific material, desired surface finish, and component geometry to achieve consistent and high-quality results.

Several theories have been proposed to explain the surface leveling mechanism in electropolishing [10]. Jacquet's theory, known as the "viscous film theory," offers a simplistic view, suggesting that the dissolution products form a thick layer on the metal surface, restricting further dissolution by limiting the current, with the film being flat on the outer surface but uneven in thickness across the material. Elmore expanded on this by incorporating diffusion, proposing that electropolishing smooths surfaces due to concentration gradients of dissolved metal ions, where peaks dissolve faster due to steeper gradients caused by slower diffusion rates. Edwards introduced an alternative model, asserting that the process is governed by the diffusion of anionic acceptors (such as phosphate ions) from the electrolyte to the anode surface, with faster dissolution occurring at protrusions where the viscous layer is thinner. Hoar later proposed a widely accepted theory involving a passive oxide film's continuous formation and dissolution on the anode. This film, formed under applied potential, prevents crystallographic etching as the metal first oxidizes and then dissolves into the electrolyte. Depending on the current density plateau, this may occur with or without oxygen evolution.

Electropolishing produces significant heat due to Joule heating and exothermic electrochemical reactions, which can destabilize the electrolyte, degrade surface quality, and cause uneven material removal if not properly managed [12-14]. Conventional cooling methods such as external chillers, cooling jackets, and synthetic coolants offer partial thermal regulation but often fall short in maintaining uniform temperature distribution, especially in continuous or high-load operations. Moreover, many synthetic coolants pose environmental concerns due to their toxicity and non-biodegradability. In response to these limitations, bio-nanocoolants have emerged as a promising alternative. These coolants combine biodegradable base fluids—such as vegetable oils or natural esters—with nanoparticles like Al_2O_3, TiO_2, or CuO to enhance thermal conductivity and fluid stability. Bio-nanocoolants contribute to improved process control by enhancing heat transfer, lowering the chance of localized hot spots, and providing a non-corrosive, environmentally safe medium. These qualities place them in line with sustainable manufacturing goals and make them particularly attractive for advanced electropolishing operations.

In recent years, electropolishing itself has seen notable innovations in both methods and materials, leading to better surface finishes, higher energy efficiency, and reduced environmental impact. One example is plasma electrolytic jet polishing (PEP-Jet), which has been reported to decrease surface roughness from Sa = 249 nm to 81 nm and cut corrosion rates by nearly 99.7%, all while using less energy than traditional approaches [15]. Research on low-current-density electropolishing of 304 stainless steel further shows that careful adjustment of electrical and bath conditions can produce smooth finishes and encourage the development of protective passive layers [16]. For additively manufactured components, two-step protocols have proven effective: a mild initial polish followed by a higher-current treatment has been shown to smooth complex geometries [17] successfully. A growing body of green electropolishing research further demonstrates that choline chloride–based Deep Eutectic Solvents (DESs) can achieve ultra-smooth finishes (~10 nm Ra) on biodegradable Fe–Mn–C alloys while minimizing corrosion and environmental impact [18].

Finally, industrial-scale considerations have emphasized the importance of controlling electrolyte contamination to prevent defects such as “orange peel” textures during large-batch operations [19]. Collectively, these developments reflect a trend toward more efficient, precise, and environmentally responsible electropolishing technologies. In recent years, there has been increased focus on optimizing the process by integrating advanced electrolytes and enhanced cooling systems—such as bio-nanocoolants—to improve consistency, reduce environmental impact, and minimize thermal degradation of the electrolyte and the workpiece.

2.1. Nanoparticle-Based Coolants Compared to Traditional Coolants

While traditional cooling methods are widely used in electropolishing, they present significant drawbacks, especially in the context of modern, high-efficiency, and environmentally conscious manufacturing. One major limitation is their inadequate thermal conductivity and slow response time, which can result in uneven temperature distribution and localized overheating, compromising polishing quality.

Additionally, many synthetic coolants pose environmental and health risks due to their toxicity, non-biodegradability, and challenges in safe handling and disposal, conflicting with green manufacturing standards [20-22]. These systems also demand high energy input and regular maintenance, increasing operational costs due to electricity consumption and the need to prevent issues like leaks or corrosion. In this context, bio-nanocoolants have gained attention as a next-generation solution, offering enhanced heat transfer, biodegradability, and the potential to improve electropolishing outcomes in both technical and ecological terms. Table 2 illustrates the role of nanoparticles in enhancing the efficiency of conventional coolants.

Table 2. Impact of nanoparticles on enhancing the performance of conventional coolants

Aspect	Conventional Cooling Techniques	Nanoparticles	Citation
Cooling Mechanism	Relies on bulk heat transfer via chillers, fans, or water jackets	Enhanced heat transfer via nanoparticle interaction at the nanoscale	[20]
Thermal Conductivity	Limited by the thermal properties of base fluids (e.g., water, synthetic oils)	Significantly improved due to the high thermal conductivity of nanoparticles.	[21]
Response Time	Slow response to sudden thermal fluctuations	Rapid heat dissipation and better thermal regulation	[22]
Environmental Impact	Often non-biodegradable, toxic, and energy-intensive	Bio-based fluids are biodegradable and less toxic	[23]
System Complexity	Requires bulky chillers, pumps, and heat exchangers	Simpler systems are possible due to enhanced fluid performance	[24]
Energy Consumption	High, due to mechanical components and continuous operation	Lower, due to more efficient heat transfer with a smaller volume and reduced reliance on mechanical cooling	[25]
Corrosion Risk	Higher, especially with synthetic or petroleum-based coolants	Reduced, especially with properly formulated bio-nanocoolants	[26]
Stability and Maintenance	Requires frequent monitoring, fluid replacement, and mechanical maintenance	Nanoparticles require stable dispersion, but the overall system can have lower maintenance.	[27]
Cost Considerations	Lower initial cost, but higher operational and maintenance costs over time	Slightly higher initial cost, but potential for long-term savings	[28]

Nanocoolants have demonstrated significant improvements in thermodynamic performance compared to conventional coolants. The inclusion of nanoparticles such as Al_2O_3, TiO_2, or CuO increases thermal conductivity, enhances heat transfer coefficients, and improves thermal Diffusivity, allowing for more efficient cooling. As illustrated, nanocoolants significantly enhance thermal conductivity, often by 15–40%, which improves overall heat transfer efficiency [29, 33]. Although the specific heat capacity of nanocoolants is slightly reduced due to the presence of solid nanoparticles, the overall heat transfer performance remains superior. The addition of nanoparticles also increases fluid density and viscosity, which can affect flow behavior and pumping requirements, as can be seen in Table 3.

Table 3. Comparison of the thermodynamic properties of nanocoolants and conventional coolants

Property	Conventional Coolants (e.g., Water, Ethylene Glycol)	Nanocoolants (e.g., Water + Al_2O_3, TiO_2, CuO)	Remarks
Thermal Conductivity (W/m·K)	Water: ~0.6–0.7; EG: ~0.25–0.4	↑ ~0.7–1.2 (15–40% increase)	Significant enhancement with nanoparticles like Al_2O_3 or CuO [21, 29]
Specific Heat Capacity (J/kg·K)	Water: ~4180; EG: ~2400–2600	↓ ~3600–4000	Slightly lower due to the presence of solid particles [30]
Density (kg/m³)	Water: ~998; EG: ~1110	↑ ~1020–1200 (5–15% increase)	Heavier due to nanoparticle loading [31]
Viscosity (mPa·s)	Water: ~0.89; EG: ~16–25	↑ 1.1–2× base fluid	Increases with concentration, may raise pumping power [32]
Thermal Diffusivity (m²/s)	~0.143 × 10^{-6} (for water)	↑ ~0.18–0.22 × 10^{-6}	Affected by conductivity and heat capacity [33]
Heat Transfer Coefficient (HTC) (W/m²·K)	~500–1000	↑ ~800–2000 (20–100% increase)	Strong gain in convective cooling performance [34]
Biodegradability	Low (petroleum-based coolants)	High (bio-based nanofluids)	Environmentally friendly [35]
Corrosiveness	Medium to High	Low (with stabilized bio-nanofluids)	Safer for stainless steel or sensitive materials [36]

3. Bio-Nanocoolants: Composition and Properties

Bio-nanocoolants are an emerging class of advanced cooling fluids designed to address both the thermal management and environmental challenges associated with conventional cooling systems. These innovative coolants combine two key components: bio-based fluids serving as the base medium and nanoparticles that enhance thermal performance [37]. The synergy between these elements results in fluids with superior heat transfer capabilities, environmental sustainability, non-corrosive properties, and high functional stability. These characteristics make bio-nanocoolants highly suitable for thermally sensitive processes such as electropolishing, where precise temperature control and material compatibility are critical [38].

3.1. Composition of Bio-Nanocoolants

The main composition of nanocoolants includes a base fluid, nanoparticles, surfactants, and optionally stabilizers (Figure 3). The base fluid acts as the primary heat-carrying medium. Conventional base fluids include water, ethylene glycol, and propylene glycol, while bio-based alternatives such as vegetable oils (e.g., castor oil, coconut oil), glycerin, and bio-ethanol are used for environmentally friendly applications. Nanoparticles are added to enhance thermal conductivity, improve heat stability, and, in some cases, provide catalytic activity. Common examples include Aluminum Oxide (Al_2O_3), Titanium Dioxide (TiO_2), Copper Oxide (CuO), Zinc Oxide (ZnO), Silicon Dioxide (SiO_2), Carbon Nanotubes (CNTs), and graphene nanoparticles. To prevent agglomeration and maintain uniform dispersion, surfactants such as SDS (Sodium Dodecyl Sulfate), CTAB, Span-80, and Tween-80 are used. Additionally, stabilizers may be incorporated to enhance the long-term chemical and suspension stability of the nanocoolant. An example of a bio-based nanocoolant composition is VG–TiO_2–SDS, where Vegetable Glycerin (VG) serves as the base fluid, TiO_2 nanoparticles improve thermal performance, and SDS acts as the dispersant [39].

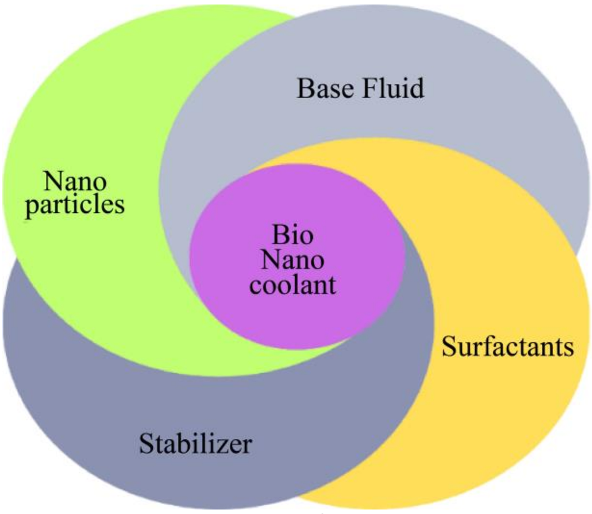

Fig. 3 Composition of bio-nanocoolant

3.2. Nanoparticles (Thermal Enhancers)

In bio-nanocoolants, nanoparticles are added to bio-based carrier fluids to boost thermal conductivity and improve overall heat transfer. These particles, which usually fall within the 1–100 nanometers range, need to be evenly distributed; otherwise, they tend to clump together, reducing stability and performance. A number of materials are commonly selected for this purpose. Aluminum Oxide (Al_2O_3) is favored because of its strong thermal conductivity and reliable chemical stability. Copper Oxide (CuO) can provide even higher thermal performance, though it requires careful handling to ensure uniform dispersion. Titanium Dioxide (TiO_2) is often chosen for its chemical inertness and occasional catalytic activity, while Zinc Oxide (ZnO) and silicon carbide (SiC) are applied in cases where better heat transfer and wear resistance are needed. To keep nanoparticles well-dispersed over time, researchers frequently rely on surface modification techniques or add surfactants such as oleic acid, sodium dodecyl sulfate (SDS), or cetyltrimethylammonium bromide (CTAB) [38, 39].

3.3. Key Properties of Bio-Nanocoolants

When nanoparticles are blended into bio-based fluids, the resulting bio-nanocoolants gain improved thermophysical and functional properties, which makes them especially useful in applications like electropolishing [40, 41]. A key advantage is the rise in thermal conductivity, allowing heat to move away from the bath or the workpiece more quickly and efficiently. In addition, improved heat capacity allows these coolants to absorb and retain more heat energy, contributing to more stable process conditions. The convective heat transfer coefficient is also enhanced due to the Brownian motion and large surface area of nanoparticles, resulting in better cooling performance. From an environmental standpoint, the eco-friendliness and biodegradability of bio-based fluids make them non-toxic and sustainable, aligning with modern regulatory and green manufacturing standards. Moreover, certain vegetable oil-based fluids provide natural lubricity and anti-fouling properties, reducing residue buildup on equipment and improving surface cleanliness. Some nanoparticles, such as TiO_2 or CuO, also offer catalytic or functional effects, potentially accelerating anodic reactions and contributing to smoother surface finishes. Lastly, advancements in formulation ensure excellent stability and dispersion quality, and prevent nanoparticle settling. Maintaining consistent thermal performance throughout prolonged use. The data presented in Table 4 demonstrates how nanocoolants outperform conventional coolants in terms of thermal conductivity and heat transfer efficiency.

Table 4. Thermal conductivity and heat transfer enhancement of bio-nanocoolant

Nanoparticle Type	Base Biofluid	Nanoparticle Concentration (% vol)	Thermal Conductivity (W/m·K)	Enhancement Over Base Fluid (%)	Source
Al_2O_3	Soybean oil	1.0	0.225	~18%	[40]
CuO	Sunflower oil	1.0	0.245	~25%	[28]
TiO_2	Palm oil	1.5	0.210	~15%	[41]
ZnO	Rapeseed oil	2.0	0.230	~22%	[42]
Al_2O_3	Bio-glycol	1.0	0.285	~20%	[35]
SiC	Ester-based fluid	0.5	0.300	~30%	[43]
CuO	Castor oil	2.0	0.265	~28%	[40]
TiO_2 + Al_2O_3 (hybrid)	Mixed vegetable oil blend	1.5	0.290	~32%	[44]

Nanoparticles in bio-nanocoolants enhance thermal performance and contribute to electrochemical and surface interaction improvements during the electropolishing process. Catalytic nanoparticles such as TiO_2 and CuO have been shown to facilitate electron transfer at the metal–electrolyte interface, thus accelerating anodic reactions and improving process efficiency [45]. Electrostatic interactions between charged nanoparticles and the metallic substrate can influence the electric double-layer structure, modulating ion transport and surface dissolution rates [46]. Furthermore, surface-modifying effects of nanoparticles may inhibit passive layer formation or promote selective dissolution, yielding smoother finishes and fewer surface defects such as pitting or etching [47]. In addition, nanoparticles modify boundary layer behavior, thinning both thermal and concentration gradients and enhancing micro-convection near the workpiece. This promotes more uniform electrolyte distribution and efficient ion diffusion, which is particularly valuable for components with intricate geometries [48]. When combined with nanoparticles, the inherent lubricity of bio-based fluids provides anti-fouling benefits such as reduced metal sludge adhesion, lower flow resistance, and cleaner post-polishing surfaces—ultimately improving process consistency and reducing maintenance demands [49, 50].

4. Effects of Nanocoolant on Corrosion Behaviour

One of the main drawbacks of nanocoolants is their potential corrosiveness. The presence of solid nanoparticles can accelerate erosion of metal surfaces, which in turn enhances corrosion–erosion effects, particularly under high-flow or turbulent conditions. Research has shown that low-corrosive nanocoolants, such as Al_2O_3/nanoparticles dispersed in vegetable oil, improve corrosion resistance on steel surfaces—mainly due to the stability of both the biodegradable base fluid and the nanoparticles [51]. CNT–water nanofluids, however, exhibit a dual behavior: at low CNT loadings (~0.1 wt%), corrosion rates can be as low as 6.43 milli-mpy, owing to the protective carbon nanotube film; yet, increasing CNT concentration and temperature significantly elevates corrosion, reaching up to 32.66 milli-mpy [52, 53]. Similarly, TiO_2-based nanofluid coatings have been observed to form passivating layers that yield very low corrosion rates; however, their effectiveness is diminished in flowing systems, where erosive forces degrade the protective layers [54, 55]. Furthermore, ZrO_2 nanofluids display greater corrosion rates at higher temperatures, indicating that temperature-driven electrochemical effects overshadow any nanoparticle protection [56]. The literature highlights that while nanocoolants can significantly enhance heat transfer, their influence on corrosion–erosion is nuanced and depends critically on factors such as nanoparticle type, loading, fluid flow, and operating temperature. As such, careful formulation and system-specific testing are essential to harness thermal benefits while avoiding material degradation.

4.1. Nanoparticle Influence on Corrosion Kinetics

Certain nanoparticles, particularly metal oxides such as CuO and TiO_2, can accelerate corrosion by acting as redox catalysts, facilitating electron transfer and enhancing metal surface anodic or cathodic reaction rates [54, 56]. Conversely, Carbon Nanotubes (CNTs) at low concentrations may inhibit corrosion by physically adsorbing onto metal surfaces and forming a protective barrier that blocks active corrosion sites, thereby reducing reaction kinetics [52, 57]. This adsorption effect follows a modified Langmuir isotherm, significantly reducing metal dissolution and oxygen reduction reactions [52]. Additionally, nanoparticles can alter the local pH at the metal surface, shifting the corrosion potentials by affecting the electrochemical equilibrium. For example, changes in boundary layer pH due to nanoparticle adsorption can influence anodic/cathodic current densities, modifying corrosion behavior [52]. However, at higher nanoparticle concentrations or temperatures, this protective barrier can become uneven, creating micro-crevices or anodic hotspots that increase corrosion risk [52, 57]. In flowing conditions, hard particles like Al_2O_3 and TiO_2 can also induce erosion–corrosion synergy by mechanically disrupting protective oxide films, thereby exposing fresh metal to aggressive conditions and accelerating degradation [54]. Overall, the impact of nanoparticles on corrosion kinetics is complex: while some nanoparticles can mitigate corrosion through barrier formation and catalytic effects, others may exacerbate corrosion, depending on concentration, flow dynamics, and temperature conditions.

The kinetics of corrosion are strongly influenced by surface roughness, as rougher metal surfaces typically exhibit faster corrosion rates. This acceleration is attributed to an increased effective surface area, which provides more active sites for electrochemical reactions, and to microstructural features such as pits and crevices that can retain moisture and corrosive agents. These features promote localized corrosion processes and can disrupt the formation of uniform passive oxide films, thereby reducing corrosion resistance. Therefore, controlling surface roughness is essential to slow corrosion kinetics and enhance long-term material durability [58, 59]. The corrosion rate increases significantly with rising surface roughness across different metallic materials and corrosive environments. For example, in Stainless Steel 316L exposed to 3.5% NaCl, the corrosion rate more than doubles from 0.05 mm/year at a surface roughness of 0.2 μm to 0.11 mm/year at 0.8 μm [60]. A similar trend is observed in Aluminium 6061 immersed in 1M HCl, where the corrosion rate increases from 0.12 mm/year at 0.3 μm to 0.27 mm/year at 1.2 μm surface roughness [61]. Magnesium Alloy AZ31 in 0.9% NaCl shows an even sharper rise—from 0.6 mm/year at 0.5 μm to 1.2 mm/year at 1.5 μm [62]. Likewise, Carbon Steel in 3.5% NaCl experiences a corrosion rate increase from 0.15 mm/year at 0.4 μm to 0.35 mm/year at 1.6 μm [63]. These findings clearly demonstrate that higher surface roughness facilitates corrosion by increasing reactive surface area and promoting localized attack.

4.2. Nanoparticle Dispersion and Stability Issues

Nanoparticle dispersion and stability are critical for maintaining the performance of nanofluids in applications like biomedical systems, coatings, and electronics. Uniform dispersion ensures a high surface area and consistent functionality, while poor stability can lead to aggregation, sedimentation, or Ostwald ripening, reducing effectiveness [64]. Studies show that surfactants such as SDS (Sodium Dodecyl Sulfate), CTAB (Cetyltrimethylammonium Bromide), and polymers like PEG (Polyethylene Glycol) and PVP (Polyvinylpyrrolidone) significantly improve dispersion and prevent agglomeration through steric and electrostatic stabilization [65, 66]. Additionally, surface functionalization using ligands like oleic acid enhances compatibility between nanoparticles and their dispersion media [67]. The choice of medium—aqueous for biomedical applications or organic solvents for electronics—further influences nanoparticle stability [68]. Effective formulation strategies that match dispersants to application requirements are essential for long-term nanofluid stability and performance [69].

5. Alternative Media for Bio-Nanoparticles in Electropolishing

Electropolishing can employ different types of coolant media, each bringing both technical benefits and environmental value. Recent studies have explored the integration of bio-based nanoparticles into systems such as ionic liquids, Deep Eutectic Solvents (DES), and even supercritical Carbon Dioxide (CO_2). When added, these nanoparticles enhance heat transfer, promote stable surface reactions, and reduce the need for harsh or toxic chemicals. Their biocompatibility and adjustable surface properties make them particularly useful in fields that demand strict safety standards, such as medical implants, food-contact components, and other environmentally sensitive applications. The next section reviews the main features of these electrolyte systems and highlights recent findings in this area of research.

5.1. Applications of Ionic Liquids as Cooling Fluids

Ionic liquids show promising potential as electrolytes and cooling media in electropolishing due to their unique physicochemical and thermodynamic properties. Several Ionic Liquids (ILs) have shown promise in electropolishing and thermal management due to their high thermal stability, low volatility, and tunable conductivity. Notable examples include imidazolium-based ILs like *[BMIM][PF$_6$], [EMIM][BF$_4$], and [BMIM][NTf$_2$]*; and sulfonium-based ILs such as *[Et$_3$S][NTf$_2$]*. Their compatibility with electrochemical systems makes them effective dual-function electrolytes and coolants. Unlike traditional acidic electrolytes such as perchloric or sulfuric acid, ionic liquids offer a safer, greener alternative, with negligible vapor pressure, non-flammability, and tunable electrochemical windows. These characteristics make them particularly appealing for precision polishing of sensitive metals like titanium, stainless steel, or aluminum, where surface quality and environmental safety are critical [70, 71]. In electropolishing, ionic liquids can function as dual-purpose agents: acting both as the electrolyte and, in some cases, as part of the cooling system—especially when combined with nanoparticles to form ionanofluids. These fluids can enhance heat dissipation, stabilize the process temperature, and contribute to smoother, more uniform material removal, reducing the risk of micro-defects or localized heating. Their ionic conductivity and wide electrochemical stability window support efficient anodic dissolution, while the absence of Volatile Organic Compounds (VOCs) supports environmentally responsible operation [72]. Recent studies have demonstrated successful polishing of metals like copper, stainless steel, and nickel alloys using ionic liquids such as choline chloride–urea Deep Eutectic Solvents (DESs) and imidazolium-based ionic liquids. These systems achieve comparable or superior surface smoothness to traditional methods while significantly lowering the ecological footprint [73, 74].

Table 5 presents a comparative overview of the thermodynamic properties of conventional coolants—such as water, Ethylene Glycol (EG), and mineral oil—and Ionic Liquids (ILs), with a focus on their suitability for thermal management and electropolishing applications. While conventional coolants like water and EG offer higher specific heat capacities and lower viscosity, ILs exhibit several distinctive advantages: exceptionally low vapor pressure, chemical tunability, high thermal and electrochemical stability, and lower environmental impact. These features make ILs particularly well-suited for use in closed-loop cooling systems and electrochemical surface treatment processes.

Table 5. Thermal performance of conventional coolants vs. Ionic liquids in electropolishing

Property	Water / EG / Mineral Oil	Ionic Liquids (ILs)	Remarks
Thermal Conductivity	Water: ~0.6 W/m·KEG: ~0.25 W/m·KOil: ~0.13 W/m·K	ILs: 0.1–0.5 W/m·K depending on type and temperature [75]	Comparable to EG; lower than water, but can be enhanced with nanoparticles
Specific Heat Capacity (Cp)	Water: ~4180 J/kg·KEG: ~2400 J/kg·KOil: ~1800 J/kg·K	ILs: typical76ly 1000–2000 J/kg·K [76, 77]	ILs have lower Cp, but are acceptable for moderate cooling loads
Viscosity (25°C)	Water: ~0.89 mPa·sEG: ~16 mPa·sOil: >30 mPa·s	ILs: 20–100 mPa·s (higher for DESs) [77]	Higher viscosity limits convective flow unless diluted or heated
Boiling Point	Water: 100°CEG: ~197°COil: >250°C	ILs: >200°C to >300°C (some stable up to 400°C) [78]	ILs offer high thermal stability and wide operating temperature ranges
Vapor Pressure	High (water), moderate (EG), low (oil)	Negligible (often $<10^{-3}$ Pa at 25°C) [70]	ILs are non-volatile—advantageous in open or vacuum systems
Corrosivity	Water/EG: Corrosive without inhibitors	ILs: Tunable; generally lower corrosivity with proper formulation [79]	ILs are compatible with corrosion-sensitive applications like electropolishing
Electrical Conductivity	Water: ~0.05 S/mEG: <0.01 S/m	ILs: 1–10 S/m depending on ion type and temperature [80]	ILs can support anodic processes while minimizing short-circuit risks
Environmental Impact	Water: benignEG: toxicOil: low biodegradability	ILs: Biodegradable ILs & DESs under development [79, 80]	ILs offer greener alternatives to petroleum-based fluids

5.2. Deep Eutectic Solvents (DES) for Electropolishing Applications

Deep Eutectic Solvents (DES) are gaining significant attention as eco-friendly alternatives to traditional coolants and electrolytes in electropolishing applications. Deep Eutectic Solvents (DES) are a class of green solvents formed by mixing two or more components—typically a Hydrogen Bond Acceptor (HBA) and a Hydrogen Bond Donor (HBD)—that interact through hydrogen bonding to form a eutectic mixture with a melting point lower than that of the individual components. Common HBAs used in DES formation include quaternary ammonium salts such as choline chloride, tetrabutylammonium chloride, tetraethylammonium chloride, and betaine. Among these, choline chloride is the most widely used due to its low cost, biodegradability, and non-toxic nature. Common Hydrogen Bond Donors (HBDs) span a wide range of organic compounds that contain hydroxyl, carboxyl, or amide groups. Examples include urea, glycerol, ethylene glycol, citric acid, lactic acid, malonic acid, oxalic acid, and even simple sugars such as glucose and fructose. Other frequently studied HBDs are phenol, thymol, and imidazole. Deep Eutectic Solvents (DES) are typically prepared by combining these donors with Hydrogen Bond Acceptors (HBAs). Well-known examples are choline chloride with urea ("reline"), choline chloride with glycerol ("glyceline"), and choline chloride with lactic or citric acid. Depending on the chosen components, these mixtures can be tuned to create hydrophilic or hydrophobic environments. Because of their low vapor pressure, adjustable properties, and overall environmental friendliness, DES have attracted growing attention in areas such as extraction, catalysis, electrochemistry, and pharmaceutical processing [70]. Their biodegradability, limited toxicity, and straightforward preparation methods make them particularly appealing for sustainable manufacturing and precision surface finishing. DES can play a dual role in electropolishing: acting as a solvent medium that supports electrochemical reactions and serving as a heat transfer fluid with moderate conductivity and good thermal stability [78]. Recent studies have shown that choline chloride–based DES can deliver polishing results that match or even surpass those of conventional electrolytes, all while reducing environmental risks [81]. Taken together, these characteristics highlight the promise of DES in advancing sustainable electropolishing practices and supporting global initiatives aimed at minimizing chemical waste and improving workplace safety. Table 6 provides a classification of DES types according to their chemical components and common applications. In general, DES are formed by mixing a hydrogen bond donor with a hydrogen bond acceptor, producing a eutectic system with a melting point lower than either of the original components.

Table 6. Types of Deep Eutectic Solvents (DESs) based on their components and applications. Formed from hydrogen bond donors and acceptors, DESs are eco-friendly solvents with tunable properties, widely used in fields such as electrochemistry, catalysis, and pharmaceuticals

Type	Components	Example System	Key Features	Applications	Ref.
Type I	Quaternary salt + Metal salt	Choline chloride + $ZnCl_2$	Ionic, metal-ion rich	Electrochemistry, metal plating	[70]
Type II	Quaternary salt + Hydrated metal salt	Choline chloride + $CrCl_3·6H_2O$	Lower viscosity, hydrated	Catalysis, metal recovery	[70]
Type III	Quaternary salt + HBD (neutral)	Choline chloride + Urea ("Reline")Choline chloride + Glycerol ("Glyceline")	Most common type, biodegradable	Extraction, drug delivery, and enzymatic reactions	[81]
Type IV	Metal salt + HBD (neutral)	$ZnCl_2$ + Urea	No organic HBA, metal-ion based	Electrodeposition, battery electrolytes	[82]
Type V	Non-ionic HBD + Non-ionic HBA	Thymol + MentholDecanoic acid + Menthol	Hydrophobic, non-ionic	Hydrophobic extractions, pharmaceuticals	[83]

Note: Quaternary salt: Typically a salt with a bulky, positively charged organic cation (like choline chloride), paired with a halide anion (like Cl^-). Quaternary salts are excellent Hydrogen Bond Acceptors (HBA).

Metal salt: A simple metal halide, such as zinc Chloride ($ZnCl_2$) or Iron Chloride ($FeCl_3$), which can also participate in hydrogen bonding and add metal ions to the mixture.

Comparing Deep Eutectic Solvents (DES) with conventional coolants (like ethylene glycol or water-based antifreeze) involves examining their thermal, chemical, environmental, and practical properties. Table 7 presents a clear comparative analysis of Deep Eutectic Solvents (DES) and conventional coolants. DES are eco-friendly, non-volatile, and low-flammable fluids with tunable properties, making them suitable for both high- and low-temperature applications. However, their high viscosity and relatively low thermal conductivity can limit their effectiveness in heat transfer systems. In contrast, conventional coolants—such as ethylene glycol-based mixtures—exhibit high thermal conductivity and dependable performance in various thermal management applications. Despite this, they are often associated with toxicity, volatility, and environmental concerns, which limit their sustainability [84].

Table 7. Comparative analysis of Deep Eutectic Solvents (DES) and conventional coolants [84]

Feature	Deep Eutectic Solvents (DES)	Conventional Coolants (e.g., Ethylene Glycol, Propylene Glycol, Water)
Thermal Conductivity	Generally lower than water or ethylene glycol	High (especially water), good for heat transfer
Heat Capacity	Lower than water, moderate to low heat storage capacity	High in water-based coolants, better for absorbing heat
Freezing Point	Very low (as low as –60°C depending on composition)	Low, depending on antifreeze mixture (e.g., –40°C)
Boiling Point	Often higher than water-based coolants	Moderate; typically 100–130°C with additives
Viscosity	Higher, especially at low temperatures	Lower; better flow properties
Volatility	Non-volatile, very low vapor pressure	Some (ethylene glycol) have moderate volatility
Toxicity	Typically low (especially choline-based DES)	Ethylene glycol is toxic; propylene glycol is less toxic
Biodegradability	High; eco-friendly (depends on components)	Varies: Propylene glycol is biodegradable; ethylene glycol is less so
Cost & Availability	Still under development, higher cost, and limited commercial availability	Cheap, widely available, well-established
Corrosivity	Can be non-corrosive or tuned for metal compatibility	Often corrosive, requiring inhibitors
Customizability	Highly tunable (component ratio, pH, polarity)	Fixed properties; customization is limited

5.3. Supercritical Carbon Dioxide (scCO$_2$)

Supercritical carbon dioxide (scCO$_2$) has been proposed as a potentially innovative and environmentally friendly alternative to conventional acid-based electrolytes in surface finishing processes. Under supercritical conditions (above 31.1 °C and 73.8 bar), CO$_2$ exhibits unique properties combining the Diffusivity of a gas with the solvating power and density of a liquid, which in theory could allow high mass transfer rates and low viscosity—advantages in achieving efficient and uniform metal surface smoothing. While many studies have explored electropolishing using ionic liquids, non-aqueous acids, and deep eutectic solvents, no confirmed studies were found that apply scCO$_2$ for electropolishing titanium or stainless steel with mild acid additives (e.g., HF or HNO$_3$). For example, Karim et al. (2020) demonstrated mirror-like titanium surfaces using deep eutectic solvents [85], while Kołkowska et al. (2024) investigated non-aqueous sulfuric acid electrolytes for Ti–6Al–4V alloys [86]. These approaches highlight greener pathways compared to traditional methods, and although scCO$_2$ remains largely theoretical in this context, its recyclability and reduced waste generation make it an attractive candidate for future research in sustainable electropolishing technologies.

5.4. Pulsed/Reverse Current Electropolishing

Research over the past few decades has shown that Pulsed Current (PC) and Pulsed Reverse Current (PRC) methods can deliver superior surface quality in electropolishing compared to conventional Direct Current (DC). For example, Datta & Landolt (1981) demonstrated in Electrochemical Machining that pulsed current regimes improve control over metal dissolution, reducing pitting and leading to smoother surfaces by regulating mass transport and limiting overheating [87]. A more recent case study on 316L stainless steel revealed that incorporating pulse or pulse-reverse current during electropolishing can reduce surface roughness and improve corrosion resistance compared to DC methods [88]. In another experiment, parameters like duty cycle and frequency strongly influenced surface finish: optimizing on/off times in pulsed current settings led to more stable passive films and fewer defects on nickel micro-moulds [89]. These findings suggest that pulsed-current-based electropolishing offers clear benefits for high-precision components, especially in sectors where surface integrity, cleanliness, and biocompatibility are critical.

5.5. Electrolyte-free Plasma Electrolytic Polishing (PEP)

Recent progress has brought notable advances in producing superior surface finishes without relying solely on corrosive electrolytes. For example, Volenko et al. studied Electrolytic-Plasma Polishing (PEP) of austenitic stainless steel using low-concentration salt solutions (e.g., ammonium sulfate, sodium carbonate) and showed that roughness can be reduced by 20–25% in comparison to conventional methods [90]. Gangqiang Ji [91] reported reductions in Ra from ~0.451 µm to ~0.076 µm using optimized voltage and electrolyte temperature. Ji, Sun, Duan, et al. (2023) [92] also demonstrated that medic-grade 316L stainless steel can have significantly improved corrosion resistance and smoother surfaces after plasma electrolytic polishing. These findings underline the potential of more environmentally benign or neutral-solution approaches in plasma electrolytic polishing as safer and sustainable alternatives for precision finishing, especially in industries where both environmental impact and surface quality are critical.

5.6. Thermal Management Techniques

Effective thermal management in electropolishing depends on a combination of systems and controls that keep operating temperatures stable and the process consistent. A common solution in large-scale facilities is the use of external cooling systems, particularly heat exchangers, which circulate water or glycol-based fluids to regulate the electrolyte temperature. Cooling jackets—double-walled tanks designed for coolant flow—provide another layer of control by maintaining a uniform bath temperature and reducing the risk of localized overheating [7, 8]. Process monitoring and feedback mechanisms also play a central role. Temperature sensors, often thermocouples paired with PID controllers, allow real-time adjustments to cooling systems to ensure conditions remain within optimal ranges. In addition, practical choices such as limiting batch size or shortening processing time can help reduce heat buildup, since smaller loads generate less thermal stress. Electrolyte circulation is another critical factor: continuous agitation and fluid flow enhance heat transfer and distribute temperature evenly, minimizing hot spots and improving stability across the bath.

5.7. Optimal Temperature Ranges

Keeping the electrolyte within an appropriate temperature range is essential for achieving quality surface finishes and maintaining process efficiency in electropolishing. Landolt (1987) proposes that optimal electropolishing often occurs under mass transport–controlled conditions, which depend on appropriate electrolyte temperature, among other variables [93]. Studies on stainless steels, such as Beamud-González et al. (2023), have shown that, for AISI 316L, an electrolyte temperature of approximately 35 °C yields good performance in terms of polishing rate, surface roughness, and electrical consumption [94]. For titanium, Peighambardoust & Nasirpouri (2014) demonstrated effective electropolishing using methanol-perchloric acid-ethylene glycol electrolytes at low temperature (near 0-5 °C in that study). These findings suggest that deviations—either too high or too low—can lead to decreased polishing efficiency, uneven surfaces, or compromised passive layers [95]. Tailoring temperature to the specific metal-electrolyte combination is critical to maintaining surface integrity and long-term finish quality.

5.8. Cooling Methods in Electropolishing

Effective thermal management in electropolishing relies heavily on the selection of an appropriate cooling method, as maintaining a stable bath temperature is essential for consistent surface quality and process efficiency. The choice of cooling method should be guided by the scale of operation, precision requirements, and thermal load. Each system offers distinct advantages, and selecting the right one plays a crucial role in optimizing electropolishing performance and overall operational efficiency. Table 8 presents four commonly employed cooling techniques suited to different operational scales and requirements. As shown in the table, immersed cooling coils are often chosen for their simplicity, cost-effectiveness, and compatibility with corrosive environments, making them a preferred option for general-purpose electropolishing across a variety of metals. For larger, industrial-scale applications, external heat exchangers provide more efficient cooling by circulating the electrolyte through an external loop. Refrigerated circulators are selected for their ability to provide precise, closed-loop temperature control, which is particularly applicable in laboratory or precision polishing environments. Lastly, chiller units are standalone systems designed to maintain a constant bath temperature over extended periods. These are commonly integrated into high-volume or automated electropolishing setups, where uninterrupted operation and long-term thermal stability are essential for quality assurance and process repeatability.

Table 8. Cooling methods used in electropolishing [91, 93, 96]

Cooling Method	Description	Common Use
Immersed Cooling Coils	Stainless steel or Teflon-coated coils circulate chilled water or glycol.	Most widely used in metal finishing.
External Heat Exchanger	Electrolyte is pumped through an external cooling loop.	Industrial-scale systems
Refrigerated Circulators	Provide precise closed-loop cooling, often used in laboratory settings.	Precision or small-batch polishing
Chiller Units	Standalone units are used to maintain a constant bath temperature.	High-volume or automated setups

5.9. Additional Considerations in Thermal Management

Beyond temperature control for process stability, several additional factors must be considered to ensure the effectiveness and sustainability of thermal management in electropolishing. One critical aspect is bath composition monitoring: elevated operating temperatures accelerate the dissolution of metal ions such as iron and chromium into the electrolyte, increasing viscosity and altering conductivity over time, which leads to inconsistent polishing outcomes and demands more frequent bath maintenance or replacement. Thermal management also directly influences energy efficiency; increases in temperature reduce electrolyte viscosity and thus improve ionic transport, but the associated heating/cooling systems can make energy costs significant if not optimized [93]. Moreover, environmental and safety concerns are central to thermal management, especially for acidic electrolyte systems [97]. Elevated temperatures increase vapor emissions and the formation of acid mist; adequate ventilation and control systems are required to comply with safety and environmental regulations. Therefore, a holistic approach to thermal management must balance performance optimization with resource efficiency and regulatory compliance [98].

6. Conclusion

The integration of bio-nanocoolants—nanoparticle-based coolants derived from bio-based fluids—plays a crucial role in thermal management during the electropolishing process. Effective thermal control is vital, as excessive heat generation can degrade surface quality and compromise process stability. Bio-nanocoolants are an important step forward in surface finishing, combining better thermal efficiency and a reduced environmental footprint. Their use, however, is not without challenges. Formulation must be carefully managed to minimize corrosive effects while maintaining strong heat transfer and compatibility with system materials. At the same time, progress is being made on other sustainable approaches, such as incorporating nanoparticles into green electrolytes like ionic liquids and Deep Eutectic Solvents (DESs), or applying advanced techniques such as Pulsed Reverse Current (PRC) and Plasma Electrolytic Polishing (PEP). These methods offer greater control of electrochemical reactions and help reduce surface defects. Among these options, electrolyte-free PEP has gained particular attention for its ability to deliver high-quality finishes without the drawbacks of corrosive chemicals. The integration of bio-nanocoolants, eco-friendly electrolytes, and modern electropolishing techniques points toward a more sustainable model of surface treatment. Continued research and development will be critical for refining these technologies and supporting their wider adoption in industrial practice.

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- Jainal: Data curation, formal analysis, manuscript review, validation.
- Firda Herlina: Investigation, visualization, data interpretation, manuscript drafting.
- Rabiatul: Methodology development, data collection, resource acquisition, manuscript finalization.
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