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Review of Machine Coolant Disposal and Recycling Methods: Ecological and Technological Perspectives

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Abstract: This article presents a comprehensive review of methods for the disposal and recycling of machine coolants, with a particular focus on ecological and technological perspectives. Coolants, essential in various industrial processes including metalworking, play a critical role in lubrication and heat dissipation. However, once spent, they become a source of significant environmental challenges due to contamination, the presence of machining oils, and the need to comply with strict environmental regulations. The article discusses the most commonly used coolant treatment technologies, such as vacuum evaporation, oil separation, regeneration, incineration, biological treatment, and chemical processing. The review emphasizes methods suitable for small and medium-sized enterprises, considering their economic efficiency, technological feasibility, and regulatory compliance. Additionally, emerging directions for future development are identified, including biotechnology and advanced membrane processes, which may contribute to more sustainable management of coolant waste.

Keywords: metalworking fluids, coolant waste management, recycling technologies, industrial waste treatment, environmental sustainability

1. Introduction

Oil-in-water emulsions are an essential component of many industrial processes, particularly in metalworking. They serve a dual purpose: the aqueous phase provides cooling, while the oil phase ensures lubrication. Additionally, coolants help remove contaminants and metal chips, which improves machining quality and extends tool life. As a result, emulsions are consumed in large quantities, generating significant volumes of waste that pose a challenge for engineers involved in industrial waste management.

Once spent, the coolant contains not only the original oil and water phases, along with impurities and metal particles, but also machining oils that enter the emulsion during operation. These factors make coolant disposal costly, technologically demanding, and problematic in the context of the European Union's ambitious climate neutrality goals.

Moreover, existing legal regulations and growing environmental awareness are forcing manufacturers to seek effective and sustainable methods for managing this type of waste. This article aims to provide a comprehensive overview of the available methods for disposing of and treating machine coolants. It discusses technologies such as chemical and mechanical purification, as well as biological and thermal treatment methods.

2. Review Methodology

This review was conducted using a structured and reproducible methodology to ensure transparency and minimize the risk of arbitrariness in source selection. The objective was to identify, compare, and critically evaluate technologies for the disposal and recycling of machine coolants, with particular emphasis on solutions applicable to small- and medium-scale industrial operations.

A comprehensive literature search was performed between January and August 2025 using scientific databases including Scopus, Web of Science, and Google Scholar. Additional sources were identified through backward snowballing from reference lists of key papers. Search strings combined terms such as *"metalworking fluid," "coolant disposal," "oil-in-water emulsion treatment," "electrocoagulation," "membrane separation," "vacuum evaporation," "biological treatment,"* and *"advanced oxidation processes."* Both English- and Polish-language publications were considered to capture relevant regional case studies.

Publications were included if they met at least one of the following criteria:

- Peer-reviewed articles or conference papers published in indexed journals with a measurable Impact Factor or equivalent scientific credibility,
- Recent works (preferably from the last 15 years) describing technologies currently in industrial use or under active development,
- Quantitative data on performance (e.g., COD/BOD removal, energy consumption, operating cost, compliance with environmental regulations),
- Case studies or technical reports from recognized institutions (e.g., ILMA, Lawrence Livermore National Laboratory) when peer-reviewed data were not available.

Sources were excluded if they lacked methodological transparency, contained purely descriptive or anecdotal information without technical relevance, or were outdated and no longer applicable under current waste management standards. Duplicate records and work outside the scope of coolant treatment were also excluded.

Priority was given to sources from journals indexed in the JCR or Scopus, and to studies with a clearly reported experimental design, replicable methodology, and statistical validity. Where possible, results from multiple independent studies were compared to verify consistency. Seminal works predating the 2000s (e.g., Nachtman 1990) were retained only when they offered fundamental insights still relevant to present-day practices.

The final selection of literature was evaluated according to four key criteria guiding this study:

- Economic feasibility for small-scale applications,
- Technological accessibility to enterprises with limited infrastructure,
- Regulatory compliance with EU and international waste management standards,
- Environmental sustainability and the potential to mitigate negative ecological impacts.

This multistage methodology enabled the balanced integration of cutting-edge scientific research with practical considerations for small and medium-sized enterprises, resulting in a comprehensive and credible overview of available coolant disposal and recycling technologies.

3. Literature Review

Machine coolants play a vital role in the metalworking industry by providing effective lubrication and heat dissipation during machining operations. However, once these fluids are spent, a significant challenge arises—how to dispose of them safely and in compliance with regulations. Improper disposal of coolants can lead to severe environmental consequences, such as soil and water contamination, and may result in substantial costs for industrial facilities.

Modern industry employs various methods for coolant disposal that aim to recover, neutralize, or destroy these substances while minimizing their environmental impact. This article discusses the most commonly used techniques, including vacuum evaporation, oil separation, regeneration, incineration, biological treatment, and chemical processing. Each of these methods has its advantages and limitations, and their selection depends on the coolant's composition, environmental requirements, and operational costs.

The management of spent machine coolant can follow three primary pathways: regeneration, utilization, or outsourcing. Each route involves different levels of treatment intensity and technological complexity. The diagram in Fig. 1 summarizes these options, outlining the key methods associated with each strategy and highlighting their practical distinctions in industrial applications.

The following sections provide a critical overview of key treatment strategies and assess the potential of advanced technologies to enhance the sustainability of industrial coolant management.

1. Vacuum Evaporation (Distillation)

This method removes water from coolant through evaporation under reduced pressure. It enables the recovery of clean water and the concentration of oily waste, thereby reducing the volume of waste that requires further treatment. However, it requires specialized equipment and generates significant energy costs.

2. Oil Separation (Filtration, Coalescence, Flotation)

This method utilizes devices that separate oils from water and other contaminants. The recovered oils can undergo further processing, such as regeneration, while the water is treated and then discharged. The efficiency of separation depends on the chemical composition of the coolant and the technology used.

3. Regeneration and Reuse

This process involves filtration, chemical treatment, and mechanical separation, enabling multiple reuse cycles of the coolant. It reduces the cost of purchasing new coolant and minimizes waste generation. Not all coolants are suitable for regeneration—it depends on the level and type of contamination.

4. Combustion in Industrial Installations

Coolants containing oils can be incinerated in industrial furnaces with energy recovery, e.g., in cement plants. This method effectively eliminates waste but requires strict compliance with emission standards.

5. Biological Treatment

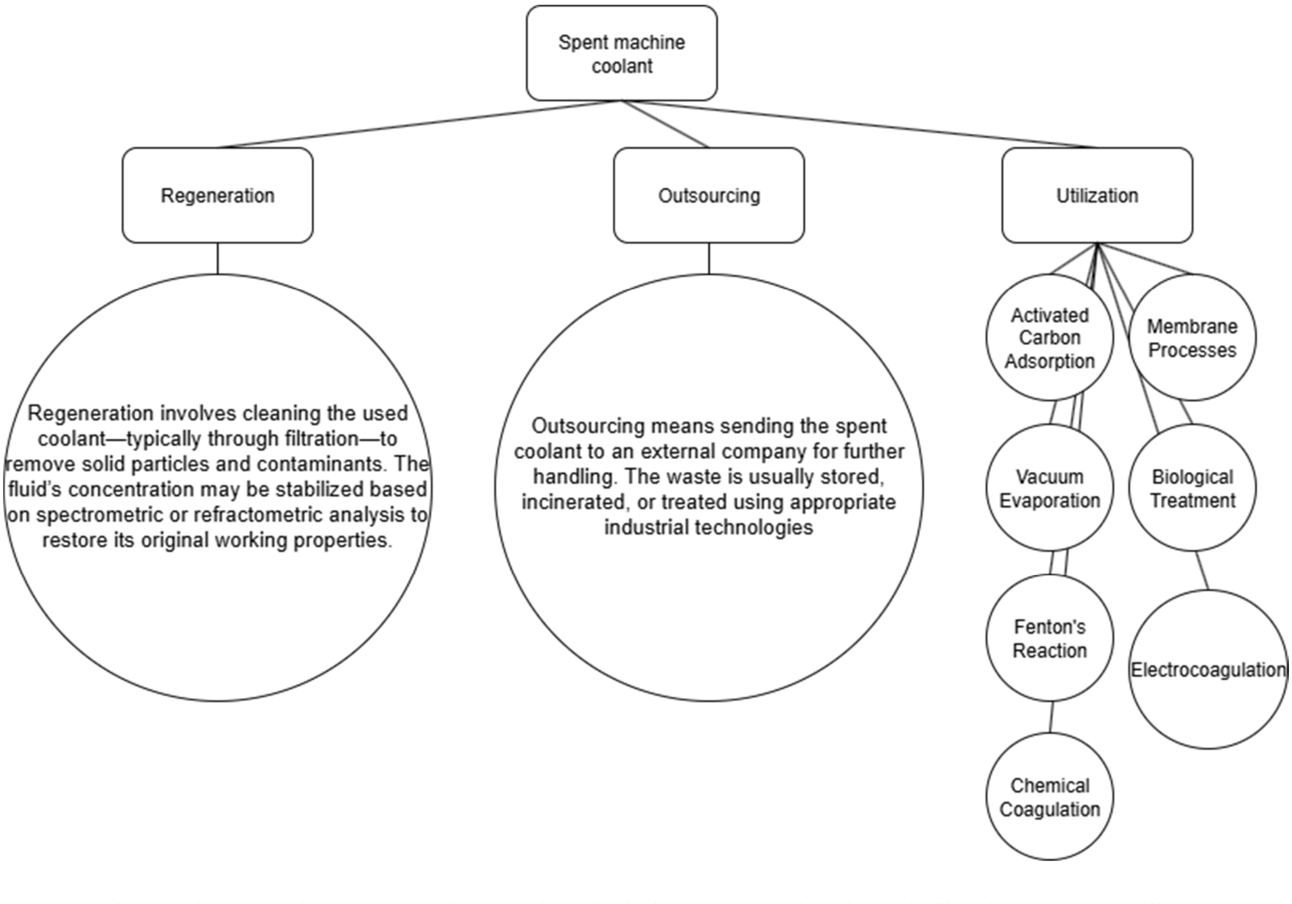
This approach uses microorganisms to break down organic substances contained in the coolant. It is primarily applied to water-rich cooling emulsions and requires precise monitoring of biological and chemical conditions to maintain process effectiveness.

6. Chemical Neutralization and Treatment

This method involves adding chemical agents to precipitate and neutralize harmful substances. It may include coagulation, flocculation, and other chemical processes for separating the components of the coolant. It requires the use of appropriate neutralizing agents and ensures their safe disposal.

7. Outsourcing to Specialized Waste Management Companies

This is the safest option for companies lacking in-house infrastructure for coolant processing. It ensures compliance with applicable legal regulations and environmental standards. However, it involves costs related to transport and external waste treatment services.



Regeneration involves cleaning the used coolant—typically through filtration—to remove solid particles and contaminants. The fluid's concentration may be stabilized based on spectrometric or refractometric analysis to restore its original working properties.

Outsourcing means sending the spent coolant to an external company for further handling. The waste is usually stored, incinerated, or treated using appropriate industrial technologies

Fig. 1. Pathways for managing spent machine coolant, including regeneration through filtration, various utilization methods (e.g., evaporation, membrane separation), and external outsourcing to specialized treatment facilities

The management of coolant waste, particularly in terms of its disposal, presents a complex challenge that requires the application of appropriate treatment technologies to meet increasingly stringent environmental standards. In recent years, there has been a global trend toward greater industrial involvement in wastewater and coolant treatment processes.

Despite the introduction of legal regulations over the years, many uncertainties still exist regarding the design of treatment systems and the selection of suitable equipment for removing contaminants from coolant fluids. These issues are critical for the industry, which must adapt its processes to comply with environmental protection laws—especially in light of growing ecological awareness and evolving legal requirements worldwide (Nachtman 1990).

Among the various coolant disposal methods, technologies aimed at separating oil-in-water emulsions—commonly generated in industrial settings—hold particular importance. These emulsions can cause serious issues, including pipe blockages, equipment corrosion, and environmental contamination such as groundwater pollution. Therefore, the effective separation of emulsions is crucial to preventing such negative environmental impacts. Techniques such as coagulation, flocculation, and various membrane-based filtration processes have proven effective in this regard. However, challenges related to the proper selection of materials and equipment for emulsion separation remain an active area of scientific research and technological development (Tian 2022, Nam 2021).

Regarding more advanced treatment methods, evaporation processes have gained popularity, especially for treating coolant fluids that contain hard-to-remove chemical substances. Studies have shown that proper control of operational parameters, such as temperature and pressure, can significantly enhance the efficiency of contaminant removal. While energy-intensive, this method is highly effective in removing chemicals with high boiling points, making it particularly relevant for industrial applications involving persistent coolant contaminants (Lipina 2021, Gutiérrez 2007).

Alternatively, membrane processes such as ultrafiltration have become important tools for treating coolant fluids, including those containing oil-in-water emulsions. Research on membrane-based separation has demonstrated high efficiency in removing oil from wastewater. Notably, the addition of coagulant salts, such as $CaCl_2$, can significantly enhance oil droplet coalescence, thereby improving separation performance. However, membrane fouling – caused by the accumulation of contaminants – remains a key challenge that limits process efficiency. To address this issue, new membrane technologies and anti-fouling strategies are being developed (Kidd 1995, Hliavitskaya 2023).

Another promising method that has attracted growing interest is the use of biotechnology for coolant treatment, particularly for removing organic contaminants such as petroleum hydrocarbons. Studies using biological reactors have demonstrated that microorganisms can effectively degrade these pollutants while achieving high removal efficiencies in terms of chemical oxygen demand (COD) and biological oxygen demand (BOD). The biotechnological approach offers a more sustainable and cost-effective solution, as microorganisms break down contaminants naturally (Muszyński 2005).

Technologies based on anaerobic co-fermentation represent an innovative approach to coolant treatment, particularly when coolants coexist with other types of waste such as manure. Research on this process has demonstrated that co-fermenting coolant fluids with manure can enhance the removal of organic pollutants, providing a promising alternative for treating industrial wastewater. In this technology, anaerobic microorganisms effectively degrade organic substances without causing adverse side effects (Rodriguez-Verde 2014).

In the context of membrane technologies, studies on ultrafiltration applied to coolant fluids have demonstrated that various operational factors—such as temperature, transmembrane pressure, and oil concentration—play a key role in process efficiency. In particular, research on ceramic membranes and their performance in oil-in-water emulsion separation indicates that optimizing operational conditions, such as pressure and temperature, can significantly improve process effectiveness (Bodzek 2013).

For the treatment of coolants contaminated with hazardous substances, including radioactive waste, simple treatment methods such as activated carbon adsorption and chemical coagulation have proven effective. Research in this area has shown that these methods can meet discharge regulations and ensure compliance with standards for hazardous waste disposal (Jagadevan 2011).

In addition to activated carbon, lignocellulosic agricultural waste materials such as wheat and rice straw have demonstrated promising adsorption capabilities for removing cutting oil from industrial wastewater. These low-cost, biodegradable sorbents achieved oil removal efficiencies exceeding 60%, with adsorption behavior following Langmuir isotherms and reaching equilibrium rapidly under optimized conditions (Kaur 2020).

Finally, the application of Fenton's reaction—a form of advanced oxidation—has gained attention as an innovative method for removing persistent organic pollutants such as oils and industrial chemicals from coolant fluids. The use of Fenton's reagent significantly enhances pollutant removal efficiency and increases the biodegradability of the treated effluent, facilitating subsequent biological treatment and reducing overall toxicity (Lobo 2006, Liu 2017).

The combined Fenton-MBR process has proven effective for treating cutting fluid wastewater with high COD and low biodegradability. Fenton oxidation enhances the biodegradability of complex pollutants, enabling the MBR system to remove residual contaminants effectively (Zhang 2017).

Among advanced coolant treatment methods, oxidation processes, such as Fenton's reaction, are gaining importance. This method, which utilizes hydrogen peroxide (H_2O_2) and iron salts (typically $FeSO_4$), has demonstrated high efficiency in degrading chemically resistant contaminants, including oil-based compounds and petroleum hydrocarbons. Studies indicate that Fenton's reaction not only effectively removes pollutants but also enhances the biodegradability of wastewater, making it more suitable for biological processes. As a result, the overall treatment becomes more efficient and environmentally friendly, aligning with modern environmental standards. The use of Fenton's process offers a viable alternative to traditional methods, particularly in cases involving heavily polluted coolant fluids, which can potentially reduce the costs and environmental impact of disposal (Vahid 2013).

Electrocoagulation (EC) has emerged as a promising technology for treating spent coolants, particularly in cases where conventional methods, such as biological treatment or chemical precipitation, prove ineffective. By employing aluminum or iron electrodes, EC enables efficient removal of suspended solids, oils, heavy metals, and organic compounds—even when the wastewater exhibits low biodegradability. Studies have shown that process performance is strongly influenced by key operational parameters, including current density, electrolysis time, pH, and the addition of supporting electrolytes, such as NaCl. Under optimal conditions, more than 65% COD removal can be achieved with relatively low energy consumption and minimal sludge production. This makes EC a viable alternative to costly incineration or illegal disposal practices, which pose significant environmental threats. Due to its effectiveness, adaptability, and potential for application to various types of industrial wastewater, electrocoagulation holds considerable promise for sustainable waste management in the metalworking industry (Pantorlawn 2018, Ng 2025).

In summary, currently available coolant treatment technologies encompass a wide range of methods, from traditional approaches such as emulsion separation to modern biotechnological and membrane-based solutions. Each method offers distinct advantages and faces unique challenges, with its applicability depending on specific industrial requirements and regulatory conditions. As the industry moves toward more sustainable practices, these technologies are expected to continue evolving, with their implementation becoming increasingly widespread and effective in the treatment and disposal of coolant fluids.

The Table 1 presents an overview of the main disposal and treatment methods for spent metalworking fluids, along with their indicative operating costs, advantages, and limitations. The data have been compiled from peer-reviewed literature and technical reports to enable a comparative assessment of technological and economic feasibility.

Although the comparative table summarizes representative cost ranges and pollutant removal efficiencies reported for individual treatment technologies, these figures must be interpreted with the utmost caution. To date, no study has systematically subjected the same wastewater stream to the entire spectrum of available treatment methods under controlled, comparable conditions. The vast majority of the literature reports focus on a single process or, at most, a narrow combination of two or three steps, each optimized for a particular influent composition, operational scale, and regulatory target. As a result, the numerical values for both operating costs and pollutant removal are inherently case-specific and cannot be directly compared across technologies without introducing significant bias.

Moreover, the wastewaters investigated across the reviewed studies exhibit substantial heterogeneity. Even within the relatively narrow class of spent metalworking fluids, major differences exist in oil fraction, surfactant and additive package, dissolved metals, pH, and baseline COD/TOC loading. Several of the data points summarized in the table originate from studies treating other types of oily or industrial effluents (e.g., refinery wastewaters, textile baths), whose contaminant profiles and biodegradability differ markedly. This variability makes direct cost-efficiency comparisons problematic: operating costs expressed per cubic meter of treated water may fluctuate by an order of magnitude depending on local energy tariffs, chemical dosing rates, labor costs, plant capacity, and the stringency of discharge limits.

Another layer of complexity arises from the fact that treatment technologies are rarely deployed as standalone solutions in real-world industrial practice. Integrated treatment trains – combining, for example, chemical coagulation with biological polishing and final filtration or evaporation – are far more common. Consequently, reported removal efficiencies and economic data frequently reflect the cumulative performance of hybrid systems rather than the intrinsic behavior of a single unit operation.

Table 1. Comparison of disposal methods

Method	Cost for MWF (USD/m³)	COD reduction for MWF (%)	Cost examples for similar wastewaters (USD/m³)	COD reduction (%)
Chemical Coagulation	0.12 USD/m³ (Demirbas 2017)	COD 65-97% (Demirbas 2017)	0.204 USD/m³ (Gasmi 2022)	54-55% (Gasmi 2022)
Electrocoagulation	1.19-1.81 USD/m³ (Demirbas 2017)	COD 68-87%, TOC 55-78% (Demirbas 2017)	0.466 USD/m³ (Gasmi 2022)	~63% (Gasmi 2022)
Membrane Processes (UF/NF/RO)	no reliable data	>99% oil removal, COD >90% after UF+NF (Hliavitskaya 2023)	0.97 USD/m³ (Rendón-Castrillón 2023)	> 80% (Rendón-Castrillón 2023)
Vacuum Evaporation	no reliable data	COD >99% (Gutiérrez 2007)	1.17-1.34 USD/m³ (Idrees 2023, Elboughdiri 2024)	~90-96% (Zhang 2022)
Biological Treatment	no reliable data	COD 74–87%, BOD >90% (Muszyński 2004)	0.39 USD/m³ (Latif 2022)	~92% (Latif 2022)
AOP (Fenton / Photo-Fenton)	no reliable data	COD 74-88%, B/C ratio up to 0.56 (Liu 2017, Zhang 2017)	13.8-14.6 USD/m³ (Solak 2023, Çalık 2022)	~85-90% (Solak 2023, Çalık 2022)
Adsorption	no reliable data	>60% oil removal (Kaur 2020) >99% oil removal (Cambiella 2006)	~1.47 USD/m³ (Hendaoui 2022, Castillo-Suárez 2023)	~60-90% (Hendaoui 2022, Castillo-Suárez 2023)
Outsourcing / Incineration	28-113 USD/m³ (Gerulová 2018)	–	Costs vary widely; no single representative value	–

Taken together, these limitations imply that the figures presented in the comparative table should be regarded strictly as indicative, order-of-magnitude benchmarks that illustrate relative trends in technical feasibility and potential cost implications. They are not suitable for direct techno-economic design, process selection, or cost prediction for a specific facility. Instead, they serve primarily as a conceptual tool to highlight the breadth of available technologies and motivate more rigorous, case-specific experimental and economic studies under standardized conditions.

3.1. Industrial case studies

To demonstrate the practical applicability beyond bench-scale experiments, representative industrial implementations across key treatment classes are summarized below. Vendor case studies and technical brochures are cited where available, while peer-reviewed reports from operating plants are included in cases where suppliers typically present only qualitative information.

Aluminum-sulfate coagulation remains a first-line step for destabilizing oil-in-water emulsions and reducing suspended solids in industrial effluents; supplier documentation emphasizes its role in emulsion breaking and sludge conditioning in full-scale wastewater operations. In parallel, deployment of real-time coagulant-dosing control (laser scattering–based) has been documented at a paper mill, cutting sludge formation by ~50% while stabilizing effluent turbidity—illustrating current practice in optimizing chemical use at scale (Ecovyst 2023).

Packaged EC systems are in service for high-strength industrial streams where emulsified oils, color, and metals constrain conventional clarification. Vendor case studies report integration at fish/poultry processing, paints/pigments, and textile facilities, with single-pass EC achieving substantial TSS/FOG/COD reduction and enabling downstream polishing or reuse; commercial spec sheets detail treatment envelopes for emulsified oil, refractory organics, and metals in industrial reuse projects (Genesis Water Technologies 2018).

Tubular UF is routinely applied to oily machining wastewater; a widely reported installation at Whirlpool's Clyde (OH) plant uses Koch/Kovalus FEG-PLUS® tubular modules to concentrate tramp oil and produce a permeate suited for further treatment, with long service life under high-fouling conditions. Datasheets and trade press describe the same platform across metalworking, food, and pulp & paper, while broader UF→NF/RO trains are increasingly used for internal recycle and paint-shop water (Watertech Online 2019).

Thermal and MVC evaporators are widely implemented for coolants, grinding swarf liquors, and mixed fabrication rinse waters, typically reducing liquid waste volumes by more than 90% and enabling water reuse. Multiple ENCON case studies (optics, vehicle wash, metal finishing) quantify the operational and disposal savings realized after retrofit. For zero-liquid-discharge objectives or high-TDS feeds, vacuum distillation units (e.g., H2O GmbH VACUDEST®) are deployed as end-of-pipe concentrators, often after primary separation. Where low-grade heat is available, membrane distillation has been piloted at textile plants toward ZLD integration (H2O GmbH 2023).

Biofilm carriers in MBBR retrofits are utilized to enhance nitrification/denitrification capacity without requiring civil expansion; refinery case studies demonstrate acclimation to high-chloride, high-TDS wastewaters with fully stainless/hyper-duplex internals. For mixed industrial/municipal loads, supplier case studies show MBBR trains meeting total-N limits at elevated influent variability. SBR platforms remain common where batch operation and footprint flexibility are advantageous, with vendors reporting hundreds of industrial and municipal installations worldwide (Veolia Water Technologies 2022).

At operating plants, Fenton pretreatment is used where toxicity or recalcitrance inhibits downstream biology. A multistage flocculation–Fenton train at a Samsung manufacturing site treated spent cutting-oil emulsions to below discharge limits, while a high-temperature, semicontinuous Fenton process at a power-plant pipeline-cleaning facility achieved >90% COD removal and restored biodegradability for subsequent aerobic polishing—illustrating two distinct industrial deployment modes (ambient multistage vs. elevated-temperature pretreatment) (Yuan 2016).

Granular activated carbon (GAC) systems are routinely used as polishing steps for organics and trace contaminants in reuse schemes. Vendor white papers and case studies document refinery VOC abatement and large-flow liquid-phase applications, with spent carbon routinely sent for thermal reactivation to minimize lifecycle costs and liability. Additional case studies show full-scale GAC removal of perfluoroalkyl substances, featuring field-verified breakthrough data and vessel configurations (Calgon Carbon Corporation, 2013).

Where on-site treatment is impractical, industries rely on off-site thermal destruction or co-processing in cement kilns. Service providers operate permitted hazardous-waste incinerators for liquids and sludges; in parallel, co-processing of compatible wastes as alternative fuels and raw materials is established at cement works, with documented plant-level case studies (e.g., Holcim Retznei) demonstrating high thermal substitution and acceptance of solvented/oleaginous streams under strict quality control. Collection and recycling logistics for used oils/antifreeze are typically provided by specialized operators as part of an outsourcing model (Veolia North America 2024).

4. Discussion

The management of machine coolant waste represents one of the key challenges in the modern metalworking industry. This article has presented a range of coolant disposal methods, including evaporation, oil separation, regeneration, incineration, biological treatment, and chemical processing. Each of these methods has its strengths, but also faces numerous challenges related to efficiency, cost, and compliance with environmental regulations. In the context of increasing environmental awareness and increasingly strict legal standards, selecting appropriate treatment technologies is crucial not only from an economic perspective but also for the sustainable development of industry.

One of the central topics discussed in this article is the effectiveness of oil-in-water emulsion separation techniques. Technologies such as coagulation, flocculation, and membrane filtration processes, including ultrafiltration, have demonstrated high efficiency in removing oil from wastewater. Nevertheless, as research has shown, these processes are still burdened by limitations such as membrane fouling, which negatively affects performance. For this reason, further development of membrane technologies is crucial to mitigate such issues. New approaches—such as the addition of coagulant salts—can enhance separation efficiency, but require adjustments to operational parameters, including temperature and pressure.

Among advanced treatment methods, vacuum evaporation stands out as an effective solution for recovering clean water and concentrating oils. While this technique is highly effective in removing persistent chemical contaminants, it is also energy-intensive and requires specialized equipment. Consequently, although evaporation may offer high treatment efficiency, its widespread adoption in small enterprises is limited. Given the regulatory emphasis on sustainable waste management, its energy demands represent a challenge that industries must consider when selecting treatment methods.

It is also important to highlight the potential of biotechnology in coolant treatment. Research on microorganisms capable of degrading organic pollutants has shown that biological methods may offer a more environmentally friendly and cost-effective alternative to conventional technologies. In particular, biotechnological approaches to removing petroleum hydrocarbons from water-rich emulsions present an effective solution. Despite their benefits, these processes require precise control of biological and chemical conditions to ensure their efficiency—a challenge that may pose a significant obstacle for small businesses with limited resources.

Another key point in the discussion is the need for compliance with environmental regulations, which require companies to adapt their processes to meet evolving standards. Despite technological advancements, uncertainties persist regarding the design of treatment systems and the selection of suitable equipment for removing contaminants from coolant fluids. Moreover, changing legal frameworks—particularly within the European Union—have a significant influence on the choice of treatment methods. Industries must continuously monitor these changes and adjust their technologies to maintain regulatory compliance.

In conclusion, the available technologies for coolant treatment offer a wide range of solutions that can be applied depending on waste characteristics and industrial requirements. Despite considerable technological progress, not all methods are suitable for every company, especially for small enterprises with limited resources. This requires flexibility in selecting appropriate technologies, as well as continued investment in scientific research to develop more effective, sustainable, and cost-efficient treatment methods. Ultimately, the choice of treatment strategies depends on multiple factors, including operational costs, technology availability, system complexity, regulatory compliance, and the broader goal of achieving climate neutrality.

5. Conclusions

The findings of this review on available machine coolant disposal methods indicate that the choice of an appropriate treatment technology depends on several key factors, including the type of coolant, the scale of production, environmental requirements, and operational costs. Current technologies—such as oil separation, vacuum evaporation, regeneration, and incineration—offer a range of options, each with its own set of challenges.

Oil separation, although effective, requires careful adaptation of the technology to the chemical composition of the coolant, which can be problematic in the case of complex emulsions. Evaporation, while highly efficient, is associated with significant energy consumption. Coolant regeneration may be limited by the level of contamination, and incineration, although capable of fully eliminating waste, must meet strict emission standards, which may pose regulatory challenges in certain regions.

Biological methods, such as treatment with microorganisms, represent a more sustainable alternative, but their effectiveness depends heavily on environmental conditions and the nature of the pollutants. Membrane technologies, particularly ultrafiltration, are gaining popularity and show promising results in separating oil-in-water emulsions, although they too face limitations related to membrane fouling.

In the context of increasing environmental awareness and evolving legal regulations that emphasize sustainable waste management, further development of coolant treatment technologies will be essential. The future is likely to bring more integrated approaches that combine various methods, enabling more efficient and environmentally friendly coolant processing. These technologies are critical to achieving sustainable industrial development and reducing the negative environmental impact of manufacturing activities.

6. Future Perspectives and Research Directions

The continuous evolution of industrial requirements, combined with increasingly stringent environmental regulations, underscores the need for a more comprehensive approach to coolant waste management. Future research should not only focus on incremental improvements to individual technologies but also on the development of integrated, multistage treatment systems capable of achieving high removal efficiencies while minimizing operational costs and secondary pollution. Hybrid processes—combining electrocoagulation with membrane filtration, or advanced oxidation with subsequent biological polishing—offer particular promise, as they have the potential to exploit synergistic effects between physicochemical and biological mechanisms. The hypothesis emerging from the reviewed literature is that properly configured hybrid systems can outperform single-stage treatments by simultaneously reducing chemical oxygen demand (COD), sludge generation, and energy consumption. Further experimental work is required to determine optimal operational parameters, including current density, transmembrane pressure, and pH, as well as to assess the long-term stability and economic viability of such solutions under real industrial conditions.

A significant trend anticipated to transform the field is the integration of artificial intelligence (AI) and machine learning techniques into process control and technology selection. Decision-support systems based on predictive models can analyze the composition of spent coolant, historical performance data, and economic constraints to propose the most suitable treatment pathway in real-time. Beyond technology selection, AI can also enable dynamic process optimization, for example, by continuously adjusting electrolysis current, temperature, or coagulant dosage to maintain peak efficiency and prevent membrane fouling. Research questions that arise from this paradigm shift include the feasibility of building sufficiently robust training datasets, the interpretability of AI-driven recommendations for plant operators, and the quantification of potential energy savings compared to conventional control strategies.

Given that a substantial share of coolant waste is generated by small and medium-sized enterprises (SMEs), future investigations should focus on the development of compact, decentralized treatment systems characterized by low energy demand, minimal maintenance, and a modular design. Pilot studies conducted under real manufacturing conditions are essential for evaluating the practical applicability of such solutions, particularly in terms of compliance with emission standards, tool wear, and occupational safety. Moreover, advancing the concept of circular economy within coolant management—by enabling multiple regeneration cycles without compromising product quality—remains a key research challenge. Long-term trials should be designed to monitor the effects of repeated coolant reuse on machining precision, corrosion behavior, and microbiological stability.

Another promising avenue is the development of innovative materials and reagents to enhance process sustainability. Anti-fouling membrane surfaces, bio-based flocculants, and green neutralizing agents could significantly reduce the generation of secondary waste and occupational hazards, aligning treatment technologies with the principles of green chemistry. Finally, comprehensive life cycle assessment (LCA) and techno-economic analysis (TEA) should become standard components of future research efforts. These tools are crucial for quantifying trade-offs among treatment efficiency, energy use, greenhouse gas emissions, and costs, ultimately supporting decision-making processes aligned with the European Green Deal and climate neutrality targets. By addressing these interconnected research areas, the scientific community can accelerate the transition toward more efficient, resilient, and environmentally responsible strategies for managing coolant waste.

7. Summary

Scale of the problem and the need for action: Machine coolants, which are essential in many industrial processes, present a significant waste management challenge. Their use leads to the generation of large volumes of contaminated fluids that require appropriate treatment or recycling methods.

Treatment methods and their effectiveness: Among the available methods for coolant disposal and recycling, the most promising include oil separation, regeneration, vacuum evaporation, incineration, and biological and chemical treatment. Each of these technologies offers advantages but also presents challenges related to cost, effectiveness, and compliance with environmental standards.

Benefits of regeneration: Coolant regeneration—particularly through filtration and chemical treatment—can reduce the need for fresh coolant, lowering operational costs and environmental impact. However, not all coolants are suitable for regeneration, necessitating a case-by-case approach.

Challenges for small enterprises: Implementing advanced coolant treatment technologies can be costly for small and medium-sized enterprises, both in terms of investment and operation. Therefore, technologies must be adapted to their specific needs and financial capabilities.

Future of treatment technologies: Growing environmental awareness and increasing legal requirements are driving the industry to seek more efficient and eco-friendly solutions. Technologies such as biotechnology, advanced membrane processes, and microbe-based recycling may play a key role in the future by offering more sustainable approaches to coolant waste management.

Regulatory importance: Strict environmental protection regulations compel businesses to adopt modern coolant treatment methods. Compliance with EU and national regulations is essential to avoid penalties and minimize environmental harm.

Development potential and innovation: Ongoing changes in coolant treatment technology, along with increased investment in research and development, may lead to new, more efficient methods. Further advancement in biotechnology and high-performance filtration processes could help meet future industrial and environmental demands.

In conclusion, effective management of machine coolants requires a combination of treatment methods that balance economic and ecological considerations. These technologies must be tailored to the specific needs of companies, including small enterprises that may lack the resources to implement advanced systems. The continued development and implementation of innovative methods will be crucial to achieving sustainable industrial progress.

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