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Toxic Coolants and Sustainable Solutions: A Jordanian Case Study on Ethylene Glycol Waste, Environmental Impact, and Policy Intervention

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Abstract

Antifreeze, primarily composed of ethylene glycol, is essential for automotive cooling systems but poses serious environmental and health risks when improperly disposed. In Jordan, field surveys across 100 workshops revealed that over 70% of used coolant is discharged directly into drains or the environment, with 85% of the public unaware of its toxicity. This paper presents a case study of Jordan's coolant waste issue and proposes a national recycling framework. A techno-economic analysis shows that regenerated antifreeze can be produced at $180–270 per ton, with positive NPV over 10 years and 5 years payback period. Several recycling methods were compared in terms of cost, purity, and environmental impact. An environmental impact assessment, aligned with ISO 14001, was conducted, and a logistics model for intermediate recycling facilities was proposed for five major cities. The study concludes with policy recommendations including regulatory reform, public awareness campaigns, and environmental taxes to support system implementation.

Paper type: Research Paper

Keywords: Toxic chemical disposal, Automotive antifreeze, Ethylene glycol, Environmental hazards, Sustainable waste management.

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1. Introduction

Ethylene glycol is a widely used chemical found in antifreeze, coolants, and various industrial products such as plastics and polyester resins. While it plays an essential role in automotive and manufacturing applications, it poses a serious threat to both human and animal health due to its high toxicity, even in small amounts. Sweet-tasting, colorless, and odorless, ethylene glycol can be mistakenly consumed by animals, leading to kidney failure, liver damage, or death. Previous studies have highlighted the importance of improving waste management practices for hazardous materials like antifreeze. For example, (Shawaqfah et al., 2024) conducted a detailed analysis of wastewater treatment plant reliability in Jordan, using probabilistic models to evaluate effluent concentrations and identify key factors affecting plant performance. This approach to environmental management can serve as a valuable framework for understanding the sustainability challenges Jordan faces in handling toxic waste, such as ethylene glycol-based coolants. (Batiha et al., 2024) studied the pollution risks from toxic elements in Ma'an district's fallout dust, highlighting the environmental and health threats posed by hazardous materials. This aligns with the challenges of managing toxic waste, such as ethylene glycol-based coolants, and underscores the importance of effective recycling systems to mitigate such risks.

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In Jordan, improper disposal practices, such as pouring used antifreeze onto the ground in vehicle maintenance workshops, have created a dangerous situation for local wildlife and the environment. This article highlights the urgency of the issue and proposes an action plan aimed at environmental and animal protection organizations to reduce harm and promote safer handling of toxic substances. The engine coolant consists of a carefully balanced formulation of various chemical components. The base of the mixture includes 500 to 700 parts of water, combined with 40 to 60 parts of sodium format and 5 to 15 parts of borax. Additional corrosion inhibitors and stabilizers are incorporated, such as 0.2 to 1.5 parts of potassium molybdate, 0.5 to 1.5 parts of octane-dioic acid (suberic acid), 1 to 10 parts of sodium caprate (capric acid sodium salt), and 0.5 to 1.5 parts each of sodium nitrate and benzotriazole. Alkalinity and buffering are controlled using 1 to 3 parts of sodium hydroxide and 1 to 3 parts of sodium metasilicate nonahydrate. The antifreeze properties are provided by adding 200 to 400 parts of 1,2-propylene glycol. In one embodiment, the antifreeze concentrate composition includes 50 to 99.8 wt.% of a glycol-based freezing point depressant, which may be selected from alkylene glycols, glycol monoethers, glycerin, or mixtures thereof. To enhance stability and prevent scale formation, 0.01 to 10 wt.% of chelating agents are added. These are preferably ethylenediaminetetraacetic acid (EDTA) and/or diethylene triamine pentacetic acid (DTPA), in a proportion of 40–60 wt.% for each component. Silicate stabilizers are included to improve the corrosion resistance and stability of the coolant. A mixture of mannitol, sorbitol, and xylitol is used in a mass ratio ranging between (1–3):(1–3):(1–3), which provides improved compatibility with metal surfaces and system components over extended periods of operation (Ningbo, 2016).

The preparation method of this coolant involves multiple stages. Initially, sodium formate, borax, potassium molybdate, suberic acid, sodium caprate, sodium nitrate, benzotriazole, and sodium hydroxide are dissolved in water with continuous stirring. After achieving a homogeneous mixture, silicate stabilizers are added and fully dissolved, forming solution A. Separately, sodium metasilicate nonahydrate is dissolved in water, then mixed into solution A to create solution B. In the final step, lanthanum chloride is dissolved in water, followed by the addition of 1,2-propylene glycol and glycerol. The chelating agents are then added and uniformly mixed, along with fluorescein sodium and dimethicone. This prepared mixture is finally incorporated into solution B to form the completed engine coolant (Ningbo, 2016). The table below provides the CAS numbers for all chemical substances used in the formulation:

Table 1. Chemical components of the engine coolant and their corresponding CAS numbers

Compound	CAS Number
Sodium formate	141-53-7
Borax	1303-96-4
Potassium molybdate	13446-49-6
Suberic acid (Octane-dioic acid)	505-48-6
Sodium nitrate	7631-99-4
Benzotriazole	95-14-7
Sodium hydroxide	1310-73-2
Sodium metasilicate nonahydrate	13517-24-3
1,2-Propylene glycol	57-55-6
Glycerol	56-81-5
Fluorescein sodium	518-47-8
Dimethicone	63148-62-9
Lanthanum chloride	10099-58-8
Ethylenediaminetetraacetic acid (EDTA)	60-00-4
Diethylene triamine pentacetic acid (DTPA)	67-43-6
Sodium caprate (Capric acid salt)	1002-62-6
Mannitol	69-65-8

The developed engine coolant offers significant advantages over traditional water-based coolants. It exhibits high chemical stability, excellent antifreeze, antirust, and anti-scaling properties, and effectively protects against corrosion of ferrous metals, copper and its alloys, aluminum, and tin. Additionally, it addresses the common issue of “boiling” found in water-based coolants, enhancing operational reliability even under high-load conditions. These properties make it particularly suitable for use in military vehicles, high-performance automobiles, and heavy-duty trucks operating in extreme environments such as deserts, high-altitude regions, or cold climates.

2. Materials and Methods

2.1 Existing conditions in Jordan

In Jordan, a lack of waste management infrastructure and low public awareness, disposing of used car coolant poses serious ecological and environmental problems. Water sources and soil become contaminated when used coolant is improperly disposed of, such as by pouring it in sewage systems, dumping it on the ground, or combining it with other automotive waste. Both humans and animals are seriously in danger of health problems due to the harmful substances included in coolants, such as heavy metals and ethylene glycol. These chemicals have the potential to create films in rivers that harm aquatic life by obstructing sunlight, interfering with photosynthesis, and lowering oxygen levels (Abu-Taleb et al., 1994. Aljaradin, et al., 2012). These contaminants can also build up in the food chain, affecting aquatic life as well as people who drink tainted water or seafood. According to studies, Jordan's present waste management procedures mostly deal with municipal solid trash, failing to adequately handle hazardous elements such as spent coolant, which leads to uneven disposal methods and environmental damage (Al-Khatib et al., 2007). This is made worse by the lax enforcement of current laws and the dearth of facilities specifically designed to recycle coolant waste. Because of this, Jordan's ecosystems and public health are still seriously threatened by the inappropriate dumping of spent car coolants. To address these problems and lessen the negative effects of used car coolant disposal on the environment and animal health, it is necessary to create sustainable coolant recycling systems, enforce environmental laws more strictly, and raise public awareness (Aljaradin, et al., 2011. Al-Maaded al., 2012).

As the main chemical in car antifreeze, is harmful to the environment and widely used. Managing and recycling used antifreeze is getting more attention, especially in countries with strong environmental rules. In Europe, some projects have worked on recycling antifreeze. One example is the ReCOOL for LIFE+ project (LIFE12 ENV/SE/000292), which used steam and distillation methods to clean used antifreeze. This project successfully treated 36,000 liters and showed it could handle up to 10 million liters each year, producing clean antifreeze that could be reused. In Germany, strict laws and recycling systems have helped recover 82–89% of used antifreeze, especially under the End-of-Life Vehicles (ELV) law that requires safe handling of car waste (European Commission., 2021). In North America, especially in California, recycling antifreeze is part of hazardous waste rules. Many vehicle repair centers use machines to clean and reuse antifreeze, supported by the (U.S. Environmental Protection Agency). These steps have helped reduce pollution and support reuse in the car industry.

A study by (Zhang et al., 2021) showed that recycling antifreeze causes less pollution and costs less than making it from new raw materials. This highlights the benefits of recycling both for the environment and the economy. However, in the MENA region, including Jordan, there are no clear rules or systems for managing antifreeze waste. Most used antifreeze in Jordan is dumped into drains or thrown away with other car waste. This study looks at how Jordan could benefit from recycling antifreeze, using local data, surveys, and examples from other countries.

One of the most commonly used compounds in Jordan's transportation industry is vehicle coolant. Maintenance stations and auto shops are the main locations where waste coolants are produced. The majority of coolant replacements take place at these places, with do-it-yourself coolant changes being rare, according to a field survey that covered 100 stations and workshops. Because waste coolants can be collected through agreements with the station or workshop owners, this makes it easier to develop a recycling program. But according to the survey, disposal methods are typically insufficient, and waste coolants are routinely dumped into municipal landfills, open spaces, or drains, which could pose environmental risks. There is a chance for sustainable waste management solutions, though, as encouraging market signs indicate that several industrial facilities in Jordan are interested in acquiring waste coolants for reprocessing.

To evaluate public perception and workshop practices regarding the disposal of used antifreeze, a structured survey was conducted between March and April 2024, targeting two key groups: automotive workshops and private vehicle owners or technicians. The sample included 100 automotive workshops and 200 individuals, selected using stratified random sampling across five cities: Amman, Zarqa, Irbid, Aqaba, and Karak, based on geographic location and workshop size. The response rate was 83% for workshops (83 completed responses) and 74% for individuals (148 responses). Data collection was carried out using a standardized questionnaire comprising 20 closed-ended and 5 open-ended questions, administered through in-person interviews at workshops, online Google Forms for individuals, and phone follow-ups to ensure completeness. All responses were anonymized, coded, and validated through cross-referencing with reports from the Jordanian Ministry of Environment (2020–2023) and Greater Amman Municipality waste audits. Outliers and inconsistencies, such as unusually high disposal volumes, were clarified and excluded as necessary. The survey revealed that 85% of respondents were unaware of antifreeze’s toxicity to animals or water, 72% of workshops disposed of used coolant into open drains or municipal sewers, and 91% rejected the use of recycled coolant due to perceived safety concerns.

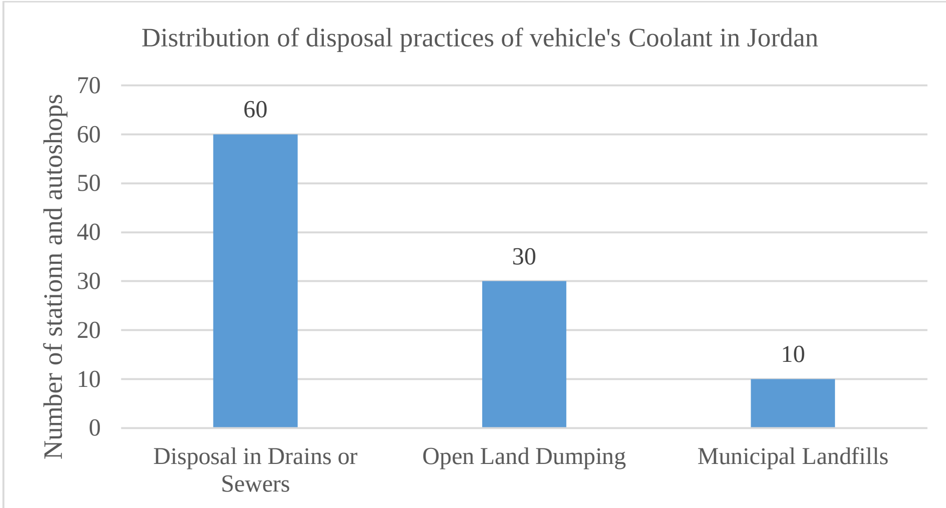

Fig. 1. Common disposal practices of used engine coolant by Auto shops in Jordan.

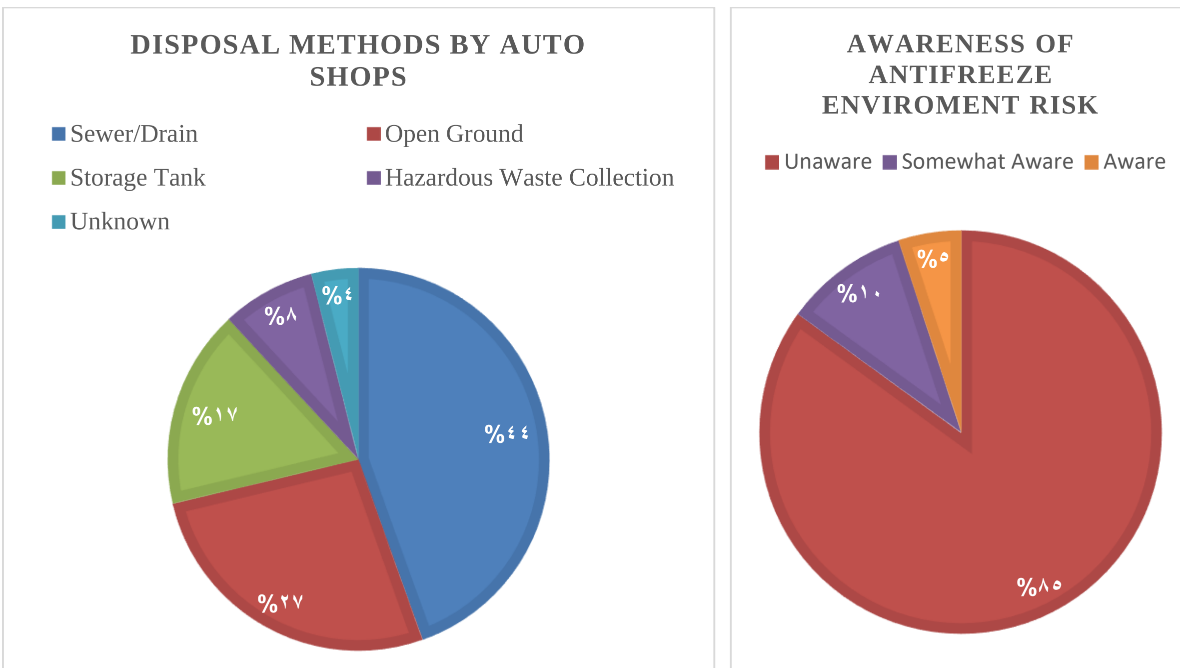

Fig. 2. Survey Results on Used Antifreeze Disposal Practices and Public Awareness in Jordan.

2.2 Net Present Value (NPV) Analysis

To evaluate long-term project feasibility, we calculate the Net Present Value (NPV) using the formula:

$$NPV = \sum_{t=1}^{n} \left(\frac{C_t}{(1+r)^t}\right) - C_0 \tag{1}$$

Where, C_t is Net cash inflow during year t, r is the discount rate (assumed 8% based on local economic average), n is the project duration (assumed 10 years), C_0 is the initial capital investment ($600,000 estimated for facility setup and equipment).

Assumed annual profit (realistic scenario): $120,000/year

Discount rate (r): 8%
Time (n): 10 years

$$NPV = \sum_{t=1}^{10} \left(\frac{120{,}000}{(1+0.08)^t}\right) - 600{,}000 \quad (2)$$

Using financial tables or spreadsheet computation:

$$NPV \approx 799{,}000 - 600{,}000 = +\$199{,}000 \quad (3)$$

A positive NPV suggests that the project is economically viable under the realistic revenue scenario, so the payback period is the time needed to recover the initial investment from net cash inflows.

$$Payback\ Period = \frac{C_0}{Annual\ Net\ Profit} = \frac{600{,}000}{120{,}000} = 5\ years \quad (4)$$

2.3 Public attitude

The survey also showed that there is a little public awareness in Jordan on coolant disposal. The idea of using recycled coolant in vehicle maintenance shops was mostly disapproved, and little to no attention was paid to the negative effects of improper coolant disposal which could have on the environment and human health. However, given that many respondents showed little understanding of the advantages and characteristics of reprocessed coolants, this problem seems to be mostly educational. Almost 85% of respondents were ignorant of the environmental risks connected to inappropriate disposal methods as well as the ultimate destination of the old coolant that was drained from their vehicles.

2.4 Recycling automotive coolants

Recycling vehicle coolants is essential for environmental protection and resource conservation. Used engine coolants, primarily composed of ethylene glycol or propylene glycol, can be processed and reused as coolants or repurposed into other products. According to the Environmental Protection Agency there are two processes in every waste antifreeze recycling method: 1) eliminating impurities using filtration, distillation, reverse osmosis, or ion exchange, and 2) using additives to restore essential antifreeze qualities. Chemicals that raise and stabilize pH, prevent rust and corrosion, lessen water scaling, and limit the decomposition of Antifreeze.

Several methods have been developed and evaluated for recycling used coolants:

1- Filtration method:

The chemical filtration technology tested for recycling spent coolant involved two units: a fleet-size unit for up to 100 gallons of stored coolant and a portable unit for vehicle-specific use without prior storage. The process includes drawing the spent coolant into a holding tank, circulating it through filters, aerating to oxidize dissolved metals, and refiltering. The portable unit also uses an ion exchange column to remove the remaining metals. The pH is adjusted to 9.5–11.0 using additives that also precipitate metals and enhance coolant quality with inhibitors, polymers, and surfactants. The freezing point is then checked, and virgin coolant is added as needed. Both units were tested with automotive and heavy-duty vehicle coolants, including "spiked" batches to evaluate the recycling process' limits. Samples were collected for analysis to assess effectiveness (Randall et al., 1993).

2- Vacuum distillation:

One important method for recycling spent industrial glycol and antifreeze is vacuum distillation, which yields high-quality ethylene glycol that can be used again. In order to separate glycol from impurities without causing undue thermal degradation, the utilised antifreeze is heated under decreased pressure, which lowers the boiling point. The vaporised glycol condenses into a pure liquid state during the process, leaving behind residues of contaminants such dissolved metals, additives, and particle debris. To improve the product's purity, post-distillation polishing procedures are used, such as filtering and chemical treatments. By lowering waste and conserving resources, this process effectively creates glycol that satisfies industry standards for the production of new engine coolants, promoting environmental sustainability (Frye et al., 1999).

3- Reverse Osmosis:

By applying pressure, the used coolant is forced through a semipermeable membrane, efficiently eliminating impurities such organic compounds, salts, and heavy metals. In order to comply with industrial standards, the refined glycol-water combination is then reformulated with corrosion inhibitors and additional additives. According to the study, RO technology can produce high-quality recycled coolant that is appropriate for use in automobiles and is both economical and environmentally friendly (Eaton et al., 1997).

4- Reverse ion:

The used antifreeze is passed through ion-exchange columns, which contain resin beads that eliminate ionic contaminants, as part of the ion exchange process for coolant recycling. By substituting innocuous ions like hydrogen or hydroxide for unwanted ones like acids and heavy metals, this efficiently filter the coolant. By restoring the coolant's chemical equilibrium, the procedure increases its resistance to corrosion and lengthens its useful life. To ensure that it can be used again in automobile cooling systems, the recycled coolant is reformulated with corrosion inhibitors and performance additives to fulfil ASTM criteria after ion exchange (Wiebe et al., 1994).

After being filtered and purified, old antifreeze is devoid of vital compounds needed to preserve engine protection and cooling system effectiveness. Reinhibition is done by adding corrosion inhibitors, foam suppressants, pH stabilizers, and anti-scaling agents to restore these qualities. To prevent acidic corrosion, coolants must first be kept within an ideal pH range, usually between 8.5 and 10.5. This is achieved by adding pH stabilizers, such as phosphates, borates, or organic acids, depending on the coolant composition. Corrosion inhibitors are then added to the engine to safeguard its metal parts. Organic inhibitors like carboxylates and azoles create protective coatings on metal components, lowering the chance of rust formation, while inorganic inhibitors like silicates and nitrites aid in protecting the surfaces of iron and aluminum. Furthermore, anti-scaling chemicals such as chelating compounds (such phosphonates or EDTA) are used to avoid mineral deposits that can reduce the effectiveness of heat transfer. Stabilisers and antioxidants are added to prolong the life of coolants by slowing down the breakdown of ethylene glycol, which can be degraded over time by oxidation. Additionally, foam suppressants, usually polysiloxane-based substances, are added to stop excessive foaming, which can cause problems with coolant circulation. Following re-inhibition, the coolant is then blended, which involves combining deionized water and purified ethylene glycol at the proper glycol-to-water ratio (such as 50:50 or 60:40) to offer suitable freeze and boil protection. After that, tests are conducted to make sure the reformulated coolant satisfies industry standards, such as ASTM D6210 for heavy-duty applications or ASTM D3306 for light-duty cars (Woyciesjes et al., 1995).

Table 2. Comparison of Coolant Recycling Methods

Method	Estimated Cost ($/ton)	Glycol Purity	Scalability	Environmental Impact	Suitability for Jordan
Filtration	100–150	Low–Moderate	Small to medium	Moderate (filter waste)	Moderate – portable but less effective
Vacuum Distillation	180–270	High	Medium to large	Low (sealed system)	High – suitable for central facilities
Reverse Osmosis	140–200	High	Medium	Low (chemical-free)	Moderate – requires membrane imports
Ion Exchange	160–220	Moderate–High	Small to medium	Low–Moderate	Moderate – depends on resin availability

Various methods are used to recycle antifreeze, each with its own advantages and limitations. Vacuum distillation provides the highest purity and is commonly used in Europe and the U.S., making it ideal for large facilities despite its high initial cost. Filtration is the most affordable option and works well for small garages or on-site recycling where high purity isn't essential. Reverse osmosis is environmentally friendly but depends on costly membranes, which may not be practical for use in Jordan. Ion exchange is also effective but requires regular replacement of resins and careful monitoring, leading to higher long-term costs.

2.5 Integrated approach

The main goal of any coolant recycling is to ensure the safe, efficient, and cost-effective collection, treatment, and disposal of used coolant, while also maintaining long-term sustainability. An integrated coolant recycling program could be the most effective approach, utilizing multiple treatment methods to reduce hazardous waste. The selection of the appropriate recycling or disposal route depends on the coolant's composition and contamination levels, making analytical testing a critical component of the process.
Several factors make coolant recycling a more viable solution:

- For different reasons, disposing the antifreeze will create a high-risk situation particularly at an environmental level.
- The transportation sector is the largest sectors in Jordan’s industry which indicates a large consumption of antifreeze in Jordan.
- Reducing the expenses of importing antifreeze to the Jordanian market.

3. Results and Discussion

3.1 Design and planning considerations

According to the justifications presented above, the main component of the antifreeze recycling strategy would be gathering and recycling used antifreeze. Three main tasks make up planning: (1) central office management of the entire process; (2) collection of used antifreeze from intermediate facilities; and (3) transportation of the collected used antifreeze to the central facility for recycling. Locating the recycling and intermediate storage facilities to save expenses, especially transportation costs, and maximize profits is a significant management system problem. Intermediate storage facilities shall be present in the six major regions where authorized private collectors transmit the used antifreeze from the automotive workshops to these facilities and then to the central facility. The central facility should be located where industrial activity is high, good transportation infrastructure and largest population. Intermediate facilities should be located in major cities so five cities were chosen:

Table 3. Potential cities in Jordan for establishing intermediate coolant recycling facilities

City	Potential Intermediate Facilities
Irbid	Large population and industrial activity in northern Jordan.
Zarqa	Large population and industrial zone.
Aqaba	Key port city with international trade links.
Mafraq	Strategic location for serving northeastern Jordan.
Karak	Serves the southern regions.

Cities for setting up antifreeze recycling centers were chosen based on how easy and cost-effective it would be to collect and transport used antifreeze. The selected cities: Irbid, Zarqa, Aqaba, Mafraq, and Karak, cover different regions of Jordan and help ensure good national coverage. Irbid has many cars and workshops, making it a key point for the north. Zarqa is close to Amman and has many factories and car services, with good road connections. Aqaba, as the main port, is useful for bringing in supplies and sending out recycled products. Mafraq links to rural areas and military services, while Karak helps cover the south, where recycling services are limited.

3.2 Economic Assessment

Any project must have an economic benefit in order to be viable. The various financial and economic elements of recycling antifreeze are discussed in this section, along with a close look at the related expenses. Three categories can be used to classify the main expenses: (1) organization and control costs incurred by the central office; (2) the final storage facility's operational and collection costs before recycling; and (3) the costs of recycling. A techno-economic model was developed to evaluate the viability of the proposed antifreeze recycling program. The total net profit per ton *NP* can be estimated using:

$$NP = R - (C_s + C_c + C_r) \quad (5)$$

Where R is the revenue per ton from recycled antifreeze, C_s is the collection and storage cost, C_c is the organizational and control cost, C_r is the recycling and treatment cost.

Assumptions:

- Revenue (R): $250–$320/ton (sale price of regenerated antifreeze based on Jordanian market interviews)
- Collection and storage (C_s): $75 – $95/ton
- Organization and admin (C_c): $55 – $80/ton
- Recycling (C_r): $180 – $270/ton

We evaluated three scenarios:

Table 4. Potential cities in Jordan for establishing intermediate coolant recycling facilities.

Scenario	Revenue (R)	Total Cost (C)	Net Profit (NP)
Optimistic	$320	$310 ($80+$95+$135)	+$10/ton
Realistic	$290	$340 ($80+$95+$165)	–$50/ton
Pessimistic	$250	$400 ($80+$95+$225)	–$150/ton

If costs exceed $290/ton, profitability depends on subsidies or environmental taxes on imported antifreeze (e.g., $35/ton tax restores breakeven).

Cost Variables Justified:

- Prices based on 2024 supplier quotes and interviews with Jordanian workshop operators.
- Revenue estimated using resale rates of antifreeze in local industrial markets (Amman, Zarqa).
- Variability factors include market demand, volume collected, and oil price impacts.

Both fixed and variable costs are included in the collection and storage costs. The purchase price from collection centers, which is estimated to be around $25 per ton, and the payment of collectors, which is set at $30 per ton, are examples of variable costs that are contingent on the amount of used antifreeze collected. Rent, maintenance, salaries, interest in capital investments, and equipment depreciation are examples of fixed costs associated with the operational management of storage facilities. According to estimates, the total cost of collecting and storing used antifreeze ranges from $75 to $95 per ton, which is like similar operations conducted abroad. Two main sources of income are produced by these activities: (1) selling collected antifreeze to businesses as a less expensive coolant substitute, and (2) imposing environmental taxes on imported antifreeze goods. According to interviews with industrial customers and auto repair shops, people are willing to pay competitive prices for recycled antifreeze as long as it satisfies quality requirements. An additional environmental tax of about $35 per ton on imported antifreeze products would be necessary to ensure financial sustainability if 4,000 tons of antifreeze were sold to industrial users each year at 50% of the market price of new antifreeze. Both variable and fixed costs are included in the recycling phase as well. While fixed costs cover staffing, maintenance, interest on capital investments, and equipment depreciation, variable costs include expenses for raw materials, chemical treatments, and transportation of regenerated antifreeze.

The total cost of these expenses for one ton of regenerated antifreeze is between $180 and $270. The business is still profitable even if it processes 6,000 tons a year, which is a conservative estimate. Because of economies of scale, higher volumes further increase profitability. However, there is a chance that the recycling operation will experience financial strain if the price of new antifreeze drops below $270 per ton. Securing stable markets and maximizing collection efficiency are crucial for reducing this risk. Unsold inventory should be managed with a backup plan that includes short-term storage for upcoming sales or export prospects to nearby markets. The storage facility may run below capacity if collection efficiency is lower than anticipated, which would raise costs per unit. Higher environmental levies on imported antifreeze, above the originally projected $35 per ton, would then be required to make up for any decrease in collection and storage costs.

Table 5. Proposed process flow diagram for used coolant collection, treatment, and recycling.

Activity	**Item**	**Cost ($ per ton)**	**Revenue ($ per ton)**
Organization and Control	Office rent, staff, administration	40–55	-
	Public awareness campaigns, subsidies	15–25	-
	Research and development	10–15	-
	Environmental tax on imported antifreeze	-	35–50
Collection and Storage	Purchase of used antifreeze (25 $ per ton)	25	-
	Collector remuneration (30 $ per ton)	30	-
	Storage facility overhead, maintenance	20–30	-
	Interest on investment	10–15	-
	Depreciation of facility and equipment	15–20	-
	Sale of collected antifreeze (reused)	-	70–90
Recycling (Regeneration)	Raw materials, treatment chemicals	80–110	-
	Transportation and logistics	40–60	-
	Staff, maintenance, facility costs	60–100	-
	Sale of regenerated antifreeze	-	250–320
Total		345–460	**355–460**

Antifreeze prices would rise by an estimated 5% as a result of the environmental tax increase required to preserve financial stability. The project would provide significant environmental benefits by reducing the disposal of hazardous waste, even though this adjustment is unlikely to have a significant impact on overall market demand. However, since antifreeze importers and distributors have a significant amount of sway over the local market, resistance from them should be expected. Overcoming possible opposition and guaranteeing the recycling initiative's long-term success will require strategic policy support and public awareness campaigns.

3.3 Requirements and public awareness for implementation

Sociopolitical factors, such as government intervention, public awareness, and regulatory enforcement, are crucial to the implementation of recycling strategies. Public awareness of antifreeze recycling is still in its infancy, as is the case in many developing nations. The idea that nature can manage waste on its own is widely held, which causes people to be careless about the dangers improper disposal poses to the environment and human health. To increase public awareness of the risks associated with used antifreeze and the advantages of recycling it, considerable environmental planning and education efforts are needed. The first step is to draw attention to how inadequate the current disposal techniques are and how they endanger public health and the environment. As demonstrated by other successful public education initiatives, such as those pertaining to disease prevention, increasing awareness of the immediate risks associated with improper antifreeze disposal can be a successful tactic. Furthermore, the public needs to be persuaded that recycled antifreeze is just as effective as brand-new antifreeze. This can be accomplished through educational campaigns that feature expert testimonials attesting to the quality of recycled antifreeze and documentary-style videos presenting the results of laboratory tests. Public trust would be further increased by endorsing and marketing the recycled product in conjunction with a respectable chemical or automotive company. Eventually, elementary school environmental education programs should incorporate antifreeze recycling and appropriate disposal techniques. Future generations will be inspired to actively engage in sustainability initiatives and cultivate a culture of environmental responsibility by early exposure to these ideas, which will ultimately improve environmental and public health.

3.4 Regulations and governmental intervention

Prior to recently, Jordan had no particular laws or rules governing the recycling and disposal of used antifreeze. Only lately have preliminary attempts been made to create rules that forbid the open disposal of spent antifreeze and specify how it should be collected and recycled. As the most efficient way to restore antifreeze for reuse, purification and reconditioning should be prioritized, followed by controlled disposal techniques to reduce environmental damage. The effectiveness of an antifreeze management strategy depends on strict laws that forbid the inappropriate disposal of antifreeze, such as dumping it in open spaces or drainage systems. Clear rules and sanctions must be in place to guarantee compliance and stop inappropriate disposal, such as pouring used antifreeze into sewage systems, which can seriously contaminate the environment. To guarantee a seamless and uniform operation across all facilities, standards for collection, storage, and recycling should be set. Although a preliminary antifreeze management framework is being created, its effective execution is essential prior to the introduction of a national recycling program.

Table 6. Comparison of Antifreeze Waste Regulations: Jordan vs. EU and USA.

Category	Jordan (Draft Framework)	European Union (EU)	United States (USA)
Legal Classification	No specific law yet; treated as general automotive waste	Classified as hazardous waste under Waste Framework Directive	Classified as hazardous waste under EPA rules
Recycling Mandate	No national recycling requirement	Encouraged under ELV Directive (2000/53/EC)	Not mandatory, but widely adopted in practice
Disposal Restrictions	Open dumping common; enforcement weak	Open disposal is prohibited; strict enforcement	Open disposal is illegal; fines apply
Authorized Facilities	Very limited infrastructure	Centralized and certified waste processors	EPA-certified facilities or on-site recycling
Public Awareness Programs	Minimal	Widespread eco-labeling and public campaigns	Supported through EPA and state programs
Incentives or Penalties	Not established	Polluter-pays principle; eco taxes	Federal & state penalties for noncompliance

Strict penalties for noncompliance are enforced in nations with established antifreeze disposal laws, guaranteeing that hazardous materials are handled appropriately. Jordan should also impose fines for careless antifreeze handling and uncontrolled dumping. To reduce the chance of contamination, antifreeze changes should only be performed by authorized auto shops. In order to preserve the effectiveness of the recycling process, collection centers should be obliged to accept only uncontaminated antifreeze.

3.5 Impact assessment of the proposed strategy

The environmental impact of used antifreeze and its recycling process was assessed in accordance with the principles of ISO 14001:2015 for environmental management systems. This assessment focused on identifying and evaluating potential risks to water, soil, and air resulting from the handling, storage, and processing of ethylene glycol-based coolant waste.

Water pollution may occur due to the discharge of used antifreeze into municipal drainage systems or unsealed ground areas, which can result in contamination of surface and groundwater resources. Similarly, soil contamination is a concern where used coolant is improperly stored or spilled during collection or transport operations, allowing toxic additives to accumulate in the upper soil layers. Air emissions from the recycling process are expected to be minimal when using vacuum distillation or sealed-loop systems, but emissions monitoring remains a recommended control measure. To address these concerns, the proposed national recycling framework incorporates sealed storage units, trained handling personnel, emergency containment protocols, and regular inspections of coolant transport and regeneration systems. These control strategies are consistent with ISO 14001:2015 requirements, particularly Clauses 6.1.2 and 6.1.4, which focus on the identification of environmental aspects and the application of operational controls to reduce negative impacts (ISO, 2015) The inclusion of these measures aims to ensure regulatory compliance while promoting continuous environmental performance improvement within the hazardous waste sector.

The suggested antifreeze recycling strategy is anticipated to have positive social effects on a number of levels. The project will have a positive economic impact in addition to improving the environment by directly creating jobs and raising tax revenues. Campaigns to raise public awareness will be launched, with the goal of promoting a culture of responsible waste management and possibly extending to more general environmental concerns. In addition to preventing long-term ecological harm, the strategy will help end the destructive practice of careless antifreeze disposal, greatly lowering soil and water contamination. The project's success will increase the legitimacy of upcoming environmental projects, which will facilitate the implementation of more sustainability initiatives. A shift toward conservation and responsible consumption will be encouraged by the realization that natural resources are finite, and public awareness and participation are crucial components of such initiatives. Furthermore, educational initiatives will foster a recycling mentality and increase confidence in the caliber and security of reconditioned antifreeze. Notwithstanding its advantages, some possible adverse effects on the environment need to be taken into account, such as:

- Used antifreeze seeping out of collection tanks.
- Spills during transit as a result of mishandling or mishaps.
- Chemical residues produced during the recycling process are improperly disposed of.
- Potential emissions from recycling plants.

Strict oversight and regulatory enforcement by a central governing body in charge of the antifreeze recycling program, however, can effectively reduce these risks. To guarantee a sustainable and ecologically responsible operation, appropriate safety procedures and best practices must be used at every level.

4. Conclusions

This study proposes a national antifreeze recycling strategy for Jordan that recognizes used antifreeze as a valuable resource while addressing the serious health and environmental risks of improper disposal. Beyond immediate economic benefits, the strategy aims to raise social awareness and promote environmental sustainability. By integrating local field data, public surveys, and international best practices, this paper presents a comprehensive environmental and economic case for establishing a recycling system. A revised techno-economic model, including cost equations, scenario analysis, and financial indicators like net present value (NPV) and payback period, provides realistic insights into the system's feasibility. A key contribution of this work is the first data-backed estimate of coolant waste disposal patterns across five major Jordanian cities, revealing widespread improper disposal and limited public awareness. The study also proposes a tailored plan for intermediate recycling hubs based on population, industrial zones, and transport efficiency.

While antifreeze recycling is technically proven worldwide, Jordan faces challenges such as weak legal regulations, limited infrastructure, market hesitation toward reused coolant, and lack of public education. To overcome these barriers, the paper recommends strong government involvement through clear disposal rules, public-private partnerships, financial incentives like import taxes on new antifreeze, and nationwide education campaigns. This framework can serve as a model for other developing countries with similar constraints. Future research should explore expanding the recycling system to other automotive fluids, applying AI for better waste tracking, and studying public behavior toward hazardous waste.

The findings confirm that antifreeze recycling is economically viable in Jordan if supported by appropriate financial tools and infrastructure. Extending the program to include packaging and resale of reconditioned antifreeze could further boost profitability and market value. Implementing this initiative is an important step for Jordan to join global efforts in recycling and resource conservation, ensuring sustainable environmental practices and long-term success through strict enforcement and public participation.

CRediT Author Contribution Statement

M. Ben Tarief: Conceptualization, Supervision, Methodology, Writing – Original Draft, Review & Editing
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The authors declare no conflict of interest.

Use of AI Tools

During the preparation of this work the author(s) used Grammarly for grammar and clarity suggestions. After using these tools, the authors thoroughly reviewed and edited the content to ensure accuracy and originality. The author takes full responsibility for the content of the publication.

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Nomenclature

Symbol/Abbreviation	Description	Unit
ASTM	American Society for Testing and Materials	—
C_0	Initial capital investment	USD
C_t	Net cash inflow during year *t*	USD
CAS	Chemical Abstracts Service (Registry Number)	—
DTPA	Diethylene Triamine Pentacetic Acid	— (chemical)
EDTA	Ethylenediaminetetraacetic Acid	— (chemical)
EG	Ethylene Glycol	— (chemical)
ISO	International Organization for Standardization	—
mg/L	Milligrams per liter (concentration)	mg/L
n	Project duration (years)	years
NPV	Net Present Value	USD
PG	Propylene Glycol	— (chemical)
ppm	Parts per million	—
r	Discount rate	%
t	Metric ton (mass); also used as subscript for year index	t
USD/t or $/ton	US Dollars per ton (cost, price)	USD/t
wt.%	Weight percent	%

For formulas:

Formula / Abbreviation	Full Name	Unit
$C_6H_6N_2$	Benzotriazole	g/L or wt.%
$C_6H_8O_6$	Mannitol	g/L or wt.%
$C_6H_{10}O_4$	Suberic acid (Octane-dioic acid)	g/L or wt.%
$C_{10}H_{20}O_2$	Sodium caprate (Capric acid sodium salt)	g/L or wt.%
H_2O	Water	L or mL
$NaNO_3$	Sodium nitrate	g/L or mol/L
NaOH	Sodium hydroxide	g/L or mol/L
$Na_2SiO_3 \cdot 9H_2O$	Sodium metasilicate nonahydrate	g/L or mol/L

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