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Reverse Logistics and Circular Economy Approach to Automotive Oil Waste Management in Panama

Alberto Alonzo-Christopher[1]; Armando Loré[2]; Guillermo Vega[3]
[1,2,3]Universidad Tecnológica de Panamá, Panamá, *alberto.alonzo@utp.ac.pa[1], armando.lore@utp.ac.pa[2], guillermo.vega1@utp.ac.pa[3]*

***Abstract*– The accelerated expansion of Panama's automotive sector has intensified the generation of used lubricating oils, classified as hazardous waste due to their heavy metal and hydrocarbon content. Although regulatory frameworks exist, compliance among workshops and service centers remains limited, creating significant environmental and public health risks. This research conducts an exploratory case study of a representative automotive service company in Panama City to examine logistical, economic, and regulatory barriers in oil waste management. Building on best international practices and circular economy principles, a strategic reverse logistics model is developed to optimize collection, treatment, and final disposal processes. The proposed model demonstrates how reverse logistics can transform hazardous oil waste management into a driver of environmental protection, regulatory compliance, and economic efficiency. The findings highlight the potential of sustainable reverse logistics systems to strengthen Panama's automotive sector while contributing to regional sustainability goals.**

Keywords- Reverse logistics, lubricating oil waste, circular economy, waste management, automotive sector.

I. Introduction

The growing Panamanian automotive sector faces significant challenges in managing used lubricating oils (ULOs), hazardous wastes that contain heavy metals and hydrocarbons. Despite the existence of environmental regulations, many workshops and service centers continue to engage in practices such as illegal dumping, inadequate storage, and informal collection, generating risks for ecosystems, public health, and long-term economic sustainability.

This study proposes reverse logistics strategies, grounded in circular economy principles, as an effective approach to improve ULO management. Through an exploratory case study of a representative automotive service company in Panama City, logistical, economic, and regulatory barriers are identified, while international best practices from countries such as Costa Rica, Colombia, and Mexico are examined to provide comparative insights.

The main contribution of this paper is the design of a strategic reverse logistics model tailored to the Panamanian context. This model aims to enhance regulatory compliance, reduce environmental and health risks, and transform hazardous oil waste into a resource that supports sustainable development in the automotive sector. By integrating reverse logistics with circular economy principles, the study highlights the potential for Panama to strengthen its waste management systems and align with global sustainability goals.

II. State of Art

A. Global Background

Current practices in reverse logistics within Panama's automotive sector reflect increasing attention to sustainability and oil waste management strategies. [1] underline the importance of effective operational risk management in reverse logistics, essential for handling used lubricating oils and mitigating environmental impacts. The complexities of oil waste management in Panama demand comprehensive reverse logistics systems capable of addressing the country's unique geographical and infrastructural challenges [3].

The Panamanian automotive industry is witnessing a growing adoption of reverse logistics processes aimed at collecting and transforming oil waste sustainably. This transformation is largely guided by regulatory frameworks and the need for companies to minimize their environmental footprint. [2] emphasize that the complexities involved in waste collection within reverse logistics significantly affect both operational efficiency and environmental outcomes. Therefore, understanding these processes is fundamental for developing more effective and efficient oil waste management strategies.

In their analysis, [1] note that training and awareness initiatives among automotive companies are fundamental to promoting adequate reverse logistics practices. These initiatives not only raise stakeholder awareness of the environmental impacts of improper oil waste management but also highlight the financial and reputational benefits associated with sustainable practices. By investing in education and training programs, companies can facilitate the correct implementation of reverse logistics processes, fostering a more circular economy in Panama's automotive sector.

B. Challenges in Implementation

Despite these advances, significant challenges remain. Limited infrastructure for waste management and inadequate recycling facilities represent serious obstacles to reversing logistics in oil waste management. The transportation of used oil to recycling centers is hindered by logistical constraints, including high costs and the dispersed distribution of collection points across the region. These barriers discourage automotive companies from fully committing to reverse logistics initiatives.

In addition, [3] propose that encouraging participation in reverse logistics programs through policy measures, such as tax incentives or subsidies, can stimulate greater involvement by automotive companies. Collaboration over stakeholders, including producers, distributors, and regulatory agencies, is essential to overcoming these challenges. Some companies have adopted innovative technologies, such as IoT-based sensors, to monitor oil waste conditions and enhance management throughout the reverse logistics process. This technological progress plays an important role in improving transparency and accountability, thereby reducing the risk of improper waste management.

In summary, while current practices in reverse logistics in Panama's automotive sector reflect a commitment to sustainability and innovation, challenges related to inadequate infrastructure, high costs, and limited stakeholder collaboration significantly affect effectiveness. Continuous research and development of context-specific solutions and advanced technologies remain necessary to strengthen these initiatives, ensuring minimal environmental impacts and the achievement of sustainability objectives.

C. Regulatory and Awareness Gaps

Challenges in implementing sustainable reverse logistics practices in Panama's automotive sector are complex and multifaceted. A prominent issue is the insufficient infrastructure necessary for effective oil waste management. [4] highlight that many automotive companies in Panama operate within inadequate logistics networks that do not support efficient collection and processing of used oil. This deficiency is aggravated by a general lack of awareness among stakeholders regarding the critical importance of reverse logistics practices. Research has revealed that many automotive operators and consumers lack knowledge of the potential environmental benefits of proper oil waste management, significantly hindering cooperative efforts for sustainable solutions.

Moreover, the absence of robust regulatory structures exacerbates these challenges. In Panama, regulatory measures governing automotive waste management are often ambiguous or weakly enforced [4]. Without a structured policy environment, companies face little incentive to invest in reverse logistics systems that prioritize sustainable outcomes. This regulatory gap makes it difficult to develop a cohesive approach to oil waste management and places undue responsibility on companies to navigate complex environmental issues independently.

D. Technological Innovation

Technological innovation represents another significant barrier to the implementation of effective reverse logistics practices for oil waste management. As highlighted by [13], Panama's automotive sector lags in adopting advanced technologies that could improve recycling and treatment efforts. Limited availability of waste treatment technologies restricts companies' ability to process used oil and affects overall sustainability. For example, the effectiveness of existing technologies in segregating oil-contaminated waste from non-contaminated materials requires optimization, a process impaired by financial constraints and the lack of partnerships with technology providers.

Environmental impacts linked to inadequate disposal methods are urgent and significant. As observed by [18], inefficiencies in current oil waste management practices can lead to severe environmental degradation, including soil and water contamination. In Panama, inappropriate disposal methods, such as illegal dumping or inconsistent recycling, contribute to pollution levels that threaten ecosystems and public health.

The involvement of informal waste collectors, while potentially improving recycling rates, complicates the reverse logistics scenario in Panama. Academic research demonstrates that informal sectors often operate outside regulatory oversight, leading to unsafe practices that exacerbate environmental issues. Integrating these actors into a formalized reverse logistics structure represents both a challenge and an opportunity for innovation.

E. Innovative Approaches and Circular Economy

Innovation plays a crucial role in improving the efficiency of reverse logistics for sustainable oil waste management in Panama's automotive sector. Research [12] highlights the importance of integrating advanced technologies and intelligent solutions to streamline reverse logistics processes. These approaches include automated monitoring systems, real-time data analysis, and IoT deployment, which collectively facilitate more effective collection, processing, and recycling of oil waste. Such technological adoption not only improves operational efficiency but also enhances accountability and transparency within the reverse logistics chain, promoting sustainable practices in the sector.

Biotransformation techniques present a promising avenue for improving oil treatment capacities. As [15] points out, biotransformation processes employ microbial activity to convert hazardous waste into non-toxic compounds, offering an alternative to conventional disposal methods. This biotechnological intervention reduces environmental impacts by mitigating soil and water contamination while creating opportunities for resource recovery, aligning with circular economic principles. Integrating these innovative waste treatment methods can facilitate a paradigm shift in how oil waste is perceived and managed in Panama's automotive industry.

Pressure from regulatory authorities and consumer expectations also plays a pivotal role in shaping reverse logistics practices. As [14] notes, environmental regulations and corporate social responsibility requirements have catalyzed the adoption of more sustainable logistics practices. Innovations such as closed-loop supply chains and product life cycle assessments allow companies not only to comply with standards but also to enhance overall sustainability performance.

F. Persistent Barriers

Despite the potential advantages of innovation, barriers persist. A lack of adequate infrastructure and limited technological capacity pose significant obstacles. Many automotive companies in Panama lack the financial or technical resources necessary to invest in sophisticated technologies or biotransformation techniques, limiting their ability to engage in effective oil waste management. Furthermore, insufficient awareness and training among industry stakeholders hinder the adoption of innovative solutions.

The fragmented nature of Panama's automotive sector, characterized by a mix of formal and informal companies, complicates collaboration efforts required for successful reverse logistics systems. This fragmentation often results in disparate practices and capacities among companies, making it difficult to establish coordinated initiatives for oil waste management. Addressing these challenges requires not only investments in innovative technologies but also holistic strategies that integrate stakeholder collaboration, policy support, and training programs to strengthen industry capacity for sustainable reverse logistics.

G. Environmental Consequences and Policy Needs

The environmental consequences of ineffective oil waste management highlight the critical need for efficient reverse logistics systems. Inefficient practices can lead to severe contamination of soil and water systems, posing risks to ecosystems and public health [7]. As Panama's automotive industry continues to expand, challenges associated with oil waste disposal have intensified. Environmental degradation linked to improper disposal methods underscores the urgency of implementing stricter regulations and practices to mitigate adverse outcomes.

[7] emphasize that inadequate attention to sustainability in supply chain operations can amplify existing environmental dilemmas. Without a solid reverse logistics framework, accumulated oil waste is often improperly disposed of, allowing hazardous materials to pollute vital community resources, including freshwater supplies. This poor management perpetuates a cycle of environmental degradation that, if not addressed, can have lasting impacts on biodiversity and public health.

Literature suggests a pressing need for Panama's automotive sector to collaborate with policymakers and industry stakeholders. By aligning industry practices with broader environmental objectives, there is an opportunity to create a more sustainable operational model. Consequently, the implementation of comprehensive national policies supporting sustainable waste management practices can encourage automotive companies to adopt responsible logistics strategies [17].

In this context, the transition toward a circular economy, characterized by reuse, recycling, and remanufacturing, emerges as an innovative solution for oil waste management. [17] argue that cooperative efforts to transform current waste logistics models within a circular economy framework could improve sustainability outcomes. Through the adoption of innovative technologies and practices, such as oil recovery and biodegradable alternatives, automotive companies could reduce their environmental footprint while benefiting economically from resource redistribution.

H. Other Considerations

Existing barriers to effective reverse logistics remain notable, including insufficient infrastructure, lack of government support, and limited industry awareness of the economic benefits of sustainable practices. The complexities of reverse logistics—from collection and transport to recycling and disposal—require coordinated stakeholder efforts. Leveraging technological advances such as blockchain and IoT can enhance traceability and efficiency across the reverse logistics chain, ensuring responsible oil waste management.

Consumer awareness and engagement also play a fundamental role in the success of reverse logistics practices. Involving consumers in oil waste recycling initiatives can cultivate a culture of sustainability, facilitating improved waste management behaviors. Empowering customers through education on proper disposal methods further aligns individual actions with collective goals of reducing oil waste and its harmful environmental impacts.

Addressing the interaction of innovative practices, stakeholder collaboration, and regulatory measures will be essential to promoting a sustainable approach to oil waste, ultimately fostering a healthier environment and a resilient economy.

TABLE I. STATE OF THE ART ON REVERSE LOGISTICS OF USED OIL

Thematic Axis	**Key Findings**		
	Findings in Literature	***Challenges Identified***	***Opportunities/ Innovations***
Infrastructure	Lack of adequate logistics networks for collection and processing [4].	Insufficient facilities and high transportation costs.	Development of specialized centers and optimization of collection routes.
Regulation	Environmental regulations are often weakly enforced [4].	Limited enforcement and lack of incentives for companies.	Clear regulatory frameworks, subsidies &fiscal incentives [3].
Awareness & Training	Training and awareness programs are crucial for improving practices [1].	Low awareness among operators and consumers regarding environmental benefits.	Environmental education, awareness campaigns, and technical training.
Technology	Low adoption of advanced technologies in the sector [13].	Limited financial and technical capacity to invest in innovation.	IoT for monitoring, blockchain for traceability [12][15].
Environmental Impact	Inadequate practices cause soil and water contamination [7][18].	Persistence of informal and illegal disposal methods.	Sustainable treatment technologies and circular economic approaches.
Informal Actors	Presence of informal waste collectors.	Risk of unsafe practices and additional contamination.	Integration of informal actors into formalized reverse logistics systems.
Collaboration	Need for cooperation among	Fragmentation of the automotive	Public-private partnerships and

Thematic Axis	Key Findings		
	Findings in Literature	***Challenges Identified***	***Opportunities/ Innovations***
	producers, distributors, and regulators [17].	sector (formal vs. informal).	regional cooperation (Costa Rica, Colombia, Mexico).
Circular Economy	Principles of reuse and resource recovery as sustainable alternatives [17].	Limited integration of circular models in business practices.	Implementation of closed-loop supply chains and life cycle assessments [14].

I. Local Background

In Panama, the management of used oils and hydrocarbon-contaminated waste was historically informal, characterized by the absence of regulation and technical capacity. These residues were often commercialized as alternative fuels for industrial boilers, practices that generated significant environmental and public health risks. The enactment of Law No. 6 of 2007 marked the introduction of the first legal framework for oily waste management, while the Zero Waste Policy (Law No. 33 of 2018) accelerated the adoption of co-processing initiatives and circular economy practices. Despite these advances, substantial gaps remain within the automotive sector, where informal handling continues to prevail. A representative automotive company in Panama City illustrates a structured approach by partnering with authorized operators to transform used oils into biodiesel and channel solid residues to specialized waste management firms. This program demonstrates the feasibility of formal systems, recovering more than 140,000 liters of oil annually, although the operational costs are absorbed under Corporate Social Responsibility (CSR) commitments. This context highlights both the progress achieved and the persistent challenges in establishing an effective nationwide reverse logistics system for oil waste management.

Similar challenges have been identified in other fields, such as the democratization of artificial intelligence, where barriers like insufficient infrastructure, high costs, and limited regulatory clarity restrict equitable access [38]. These parallels reinforce the idea that Panama's automotive sector requires inclusive policies, stakeholder collaboration, and technological innovation to establish a robust reverse logistics framework capable of ensuring sustainability and social responsibility.

III. Problem Statement

The concept of circular economy has gained significant traction in Latin America, with countries such as Costa Rica, Colombia, and Mexico actively developing policies and practices to facilitate this model. Circular economic strategies, combined with Extended Producer Responsibility (EPR) schemes, aim to create comprehensive reverse logistics systems that promote sustainable practices, mitigate waste, and increase resource efficiency. A bibliometric analysis [21] illustrates the growing body of research on this subject throughout the region, highlighting the substantial interest of governmental and academic sectors in advancing circular economy principles.

In Costa Rica, government-led EPR programs have targeted specific sectors, such as plastic waste management [22], strengthening recycling and reuse initiatives and consolidating reverse logistics systems. Colombia has embraced circular economy principles through end-of-life tire management, where pyrolysis technology is proposed as a viable solution [23]. Mexico has implemented integrated approaches to electronic waste management, supported by public policies that address the complexities of reverse logistics under EPR schemes [24][25].

Despite these advances, Latin American urban areas still face obstacles such as inadequate infrastructure and limited public awareness [26]. However, the integration of reverse logistics into EPR structures presents opportunities to overcome these barriers, particularly in critical sectors such as lithium batteries [27] and textiles [28].

In contrast, Panama's automotive industry has experienced rapid growth, significantly increasing the generation of used oils and lubricants (ULOs), hazardous wastes containing heavy metals and hydrocarbons. Current practices in workshops and service centers—including improper storage, informal collection, and illegal dumping—pose severe risks to the environment and public health. Unlike Costa Rica, Colombia, and Mexico, Panama lacks consolidated reverse logistics systems and EPR schemes, relying instead on fragmented and unsustainable practices. Limited incentives, weak enforcement, and insufficient technical capacity hinder compliance and sustainability in the sector. This study addresses these gaps by analyzing the case of a representative automotive company in Panama Province and proposing a strategic reverse logistics model tailored to national conditions.

A. What Is Known

Existing literature demonstrates that reverse logistics plays a critical role in improving environmental performance and operational efficiency in hazardous waste management systems. Studies conducted in Latin America and other emerging economies show that structured reverse logistics networks, supported by Extended Producer Responsibility (EPR) schemes and circular economy principles, can significantly reduce environmental risks associated with industrial waste streams. Research has identified key enabling factors such as regulatory enforcement, stakeholder collaboration, infrastructure availability, technological adoption (e.g., IoT-based traceability systems), and financial incentives as determinants of effective reverse logistics implementation.

In the automotive sector specifically, international studies highlight that used lubricating oils (ULOs) require formalized collection, certified handling, and traceable disposal mechanisms to prevent soil and water contamination. Countries such as Costa Rica, Colombia, and Mexico have advanced structured frameworks integrating policy instruments, public–

private partnerships, and technological monitoring systems to strengthen oil waste recovery and recycling practices.

B. *What Is Not Known*

Despite the growing body of research on reverse logistics and circular economy applications in Latin America, limited empirical evidence exists regarding the specific conditions of used lubricating oil management in Panama's automotive sector. There is insufficient documentation of how logistical, regulatory, and economic barriers interact within the Panamanian context.

Furthermore, while international best practices have been documented, little is known about their adaptability to small and medium-sized automotive workshops operating within fragmented and partially informal environments. The availability of authorized service providers, the level of regulatory compliance, and the degree of traceability in final disposal processes remain underexplored.

Most importantly, there is no context-specific strategic reverse logistics model tailored to Panama's institutional, infrastructural, and economic realities that integrates circular economy principles with operational feasibility.

C. *What This Study Contributes*

This study contributes to the literature by providing an empirical diagnosis of used lubricating oil management practices within a representative automotive company in Panama Province, identifying operational, regulatory, and infrastructural gaps.

Based on these findings and supported by regional comparative analysis, the research proposes a strategic reverse logistics model structured around five key variables: infrastructure capacity, regulatory enforcement, training and awareness, economic incentives, and digital traceability.

Unlike purely conceptual discussions, this study grounds the proposed framework in field-based evidence and adapts international best practices to the Panamanian context. By integrating reverse logistics with circular economy principles under emerging-economy constraints, the research offers a transferable model that can inform policy development, institutional strengthening, and sustainable waste management strategies in similar developing economies.

TABLE II. PRACTICES IN REVERSE LOGISTICS OF USED OIL

Dimension	**Comparative Practices**			
	Panama	***Costa Rica***	***Colombia***	***Mexico***
Regulatory Framework	Ambiguous regulations, weak enforcement, limited incentives [4].	Strong environmental policies; extended producer responsibility schemes.	Operational risk management frameworks applied to reverse logistics [2].	National programs promoting compliance and recycling through fiscal incentives.
Infrastructure	Limited recycling facilities; high transport costs; dispersed collection points.	Centralized collection systems are supported by government and private partnerships.	Development of structured logistics networks for oil waste management.	Expansion of recycling centers and integration into industrial supply chains.
Awareness & Training	Low awareness among operators and consumers; limited training programs [1].	National campaigns on sustainability and waste management.	Training programs for automotive companies to mitigate environmental risks.	Industry-wide awareness initiatives linked to corporate social responsibility.
Technology Adoption	Low adoption of IoT, blockchain, and advanced treatment technologies [13].	Use of IoT sensors for monitoring waste flows.	Application of operational risk management supported by digital tools [2].	Adoption of blockchain and ERP systems for traceability and compliance.
Circular Economy	Limited integration of circular economy principles in business practices [17].	Strong emphasis on reuse and recycling within national sustainability agendas.	Integration of circular economy principles into automotive waste management.	Circular economy frameworks promoted through government-industry collaboration.
Stakeholder Collaboration	Fragmented sector; informal collectors complicate coordination.	Public-private partnerships encourage collaboration.	Collaboration among universities, companies, and regulators.	Multi-stakeholder platforms for sustainable logistics initiatives.
Environmental Impact	Persistent soil and water contamination due to improper disposal [7][18].	Reduction of pollution through structured recycling programs.	Improved environmental outcomes via risk-based reverse logistics models.	Significant reduction in illegal dumping through enforcement and incentives.

A. *Objectives*

The objective of this study is to develop reverse logistics strategies for the sustainable management of used oils and lubricants (ULOs) in Panama's automotive industry. Specifically, the study seeks to:

- Assess the current state of ULO management practices in automotive workshops and service centers.
- Identify logistical, economic, and regulatory barriers hindering the implementation of reverse logistics systems.
- Propose a strategic model, informed by international best practices and adapted to national conditions, to optimize the collection, treatment, and safe disposal of ULOs.

B. *Justification*

Improper management of used oils and lubricants (ULOs) in Panama's automotive industry poses serious environmental, health, and operational risks. Although hazardous waste regulations exist, enforcement remains weak and informal practices are widespread, particularly in small workshops and service centers. Reverse logistics offers a structured approach to recover, treat, and safely dispose of ULOs, yet its application in Panama is still incipient due to regulatory gaps, limited infrastructure, and low technical awareness.

This research is justified by the need to close these gaps through a strategic model adapted to national conditions. Its contribution lies in integrating reverse logistics with circular economy principles to improve compliance, reduce risks, and support sustainable practices in the automotive sector. Furthermore, the study aligns with global sustainability goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

IV. Methodology

This study adopts a descriptive and exploratory design with a mixed-methods approach. Data collection combined documentary review with a structured survey administered to technical and operational staff at a representative automotive company in Panama Province.

The survey targeted employees involved in maintenance, logistics, and waste management, with the objective of diagnosing current practices, assessing knowledge of hazardous waste regulations, and capturing perceptions regarding reverse logistics. Responses were systematically categorized into thematic areas related to operational practices, regulatory compliance, and sustainability awareness.

Qualitative insights from the documentary review were integrated with quantitative survey data to provide a comprehensive understanding of existing gaps. This case-based approach offers valuable evidence to inform the design of a strategic reverse logistics model, adaptable to the broader Panamanian automotive industry and aligned with circular economy principles.

V. Results

The survey, designed as a structured expert interview, allowed the identification of key variables for the development of the reverse logistics model. The respondent, a senior manager with more than six years of experience in after-sales and logistics, confirmed familiarity with reverse logistics concepts and reported that the company maintains a formal system for the separate collection of used lubricating oils (ULOs), carried out biweekly in certified containers by authorized external providers. The interview revealed partial knowledge of the final disposal processes and incomplete compliance with national regulations, highlighting gaps in transparency and enforcement. Training programs have been implemented, and staff demonstrated awareness of environmental and health risks, although willingness to participate in additional sessions was conditioned by workload. The expert emphasized that the main challenge is the lack of adequate service providers, which limits infrastructure and service coverage. Furthermore, the interviewee suggested fiscal incentives, stricter enforcement, and awareness campaigns as measures to strengthen system effectiveness. These insights, derived from expert testimony, were categorized into operational practices, regulatory compliance, and sustainability awareness, providing the foundation for defining the critical variables of the strategic reverse logistics model proposed in this study.

The survey results confirm that a representative automotive company in Panama Province has established a formal system for the collection of used lubricating oils (ULOs). Collection is carried out biweekly using certified containers, and authorized external companies are responsible for transport and treatment. This demonstrates that, at least in larger and more structured firms, reverse logistics practices are already partially integrated into operational routines.

Staff responses revealed a high level of familiarity with reverse logistics concepts and a strong awareness of the environmental and health risks associated with improper ULO management. Training programs have been implemented, and employees reported having received instruction on safe handling and regulatory requirements. However, willingness to participate in additional training sessions was conditioned by workload and time availability, suggesting that future capacity-building initiatives must be flexible and adapted to operational constraints.

Despite these advances, compliance with national regulations was perceived as incomplete. While employees acknowledged the existence of legal frameworks, they reported only partial adherence to requirements, particularly regarding documentation and traceability of final disposal. Knowledge of the ultimate destination of collected oils was limited, indicating a gap in transparency and communication between service providers and workshops.

The main challenge identified was the insufficient availability of specialized service providers capable of covering the demand across the sector. This limitation reduces the frequency and reliability of collection services, creating risks of accumulation and potential improper disposal. Respondents emphasized the need for fiscal incentives and stronger enforcement mechanisms to encourage compliance and expand service coverage. Awareness campaigns were also recommended to reinforce stakeholder engagement and promote a culture of sustainability.

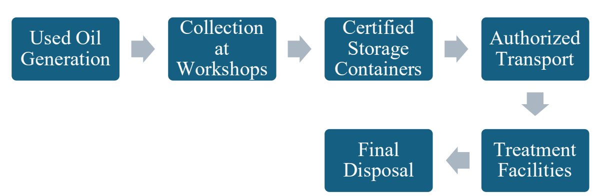

Fig. 1. Process Flow Diagram.

The results indicate that while formal collection system exists, significant gaps in regulatory compliance, service availability, and stakeholder engagement persist, underscoring the need for a strategic reverse logistics model.

TABLE III. RESULTS SUMMARY

Aspect	Findings
Collection system	Formal system in place; biweekly collection of ULOs using certified containers
Responsible party	Authorized external companies handle collection and treatment
Knowledge of final disposal	Partial understanding among staff
Regulatory compliance	Perceived as incomplete (partial compliance reported)
Training	Staff received training; willingness for additional training depends on available time
Awareness	High recognition of environmental and health risks
Effectiveness perception	Current system considered effective, though improvable
Main challenges	Lack of adequate service providers; limited infrastructure
Improvement suggestions	Fiscal incentives, stricter enforcement, and awareness campaigns

V. MODEL DEVELOPMENT

This section presents the development of a strategic reverse logistics model for the sustainable management of used lubricating oils (ULOs) in Panama's automotive sector. The model is grounded in empirical findings derived from the case study and expert diagnosis previously described and integrates reverse logistics theory, circular economy principles, and Sustainable Development Goal (SDG) alignment.

A. *Conceptual Design of the Model*

The proposed model adopts a closed-loop supply chain approach in which ULOs are considered recoverable industrial resources rather than residual waste. The model structure is based on five critical variables identified in the field research :

1. Infrastructure capacity
2. Regulatory enforcement
3. Training and awareness
4. Economic incentives
5. Digital traceability

These variables are operationalized through a four-layer system: (i) collection optimization, (ii) treatment and recovery optimization, (iii) final disposal and circular reintegration, and (iv) institutional and digital governance.

B. *Collection Optimization Layer*

The first operational layer addresses the efficient recovery of ULOs from automotive workshops and service centers. The network includes workshops (formal and informal), authorized collectors, regional consolidation hubs, and certified treatment facilities.

A zonal clustering strategy is proposed for Panama Province, dividing collection points into geographic sectors to reduce transportation inefficiencies. Route optimization follows a Vehicle Routing Problem (VRP) formulation. The objective function is expressed as:

Minimize $C_{total} = C_{transport} + C_{handling} + C_{storage} + C_{risk}$, subject to:

- Regulatory compliance constraints
- Minimum collection frequency requirements
- Certified container standards
- Hazardous material handling regulations

The inclusion of environmental risk cost (C_{risk}) internalizes potential contamination impacts, aligning operational optimization with sustainability objectives.

Digital tools such as GIS mapping and IoT-based tank sensors may be incorporated to enable real-time volume monitoring and trigger collection cycles, addressing transparency gaps identified in the empirical analysis.

C. *Treatment and Recovery Optimization*

The second layer prioritizes recovery alternatives under circular economy hierarchy principles. Treatment options are ranked as follows:

1. Re-refining into base oil
2. Biodiesel transformation
3. Co-processing in cement kilns
4. Energy recovery
5. Secure hazardous disposal (last option)

A multi-criteria evaluation framework is proposed to assess treatment alternatives using the following indicators:

- Recovery efficiency
- Environmental impact reduction
- Operational cost
- Technological feasibility
- Regulatory compliance

The model recommends the development of regional oil recovery centers to improve economies of scale and reduce transportation distances. Advanced technologies, including oil purification systems and microbial biotransformation processes, are incorporated to increase recovery rates and reduce ecological risk.

D. *Final Disposal and Circular Reintegration*

The third layer ensures that only non-recoverable wastes are directed to certified hazardous landfills. Recoverable outputs are reintegrated into industrial value chains through:

- Production of re-refined lubricants
- Alternative industrial fuels
- Substitution of virgin raw materials
- Performance indicators for circular reintegration include:
- ULO capture rate (%)

- Re-refining conversion efficiency (%)
- CO_2 emissions avoided
- Reduction in illegal dumping incidents

This structure transforms hazardous waste management into a resource recovery system, reinforcing industrial sustainability and operational resilience.

E. Governance and Digital Traceability

The fourth layer addresses regulatory and institutional gaps identified in the case study . A National Digital Oil Waste Registry is proposed to strengthen monitoring and enforcement.

Core system functions include:

- Real-time reporting of collected volumes
- Automated hazardous waste manifests
- Blockchain-enabled traceability
- Compliance dashboards for regulators
- Audit-ready documentation

Complementary policy instruments include:

- Extended Producer Responsibility schemes for lubricant importers
- Fiscal incentives for compliant workshops
- Sanctions for illegal dumping
- Public compliance transparency mechanisms

This governance backbone enhances accountability, reduces information asymmetry, and increases regulatory effectiveness.

F. SDG Integration

The model contributes directly to global sustainability objectives:

- SDG 12 (Responsible Consumption and Production): Implementation of closed-loop oil recovery systems.
- SDG 13 (Climate Action): Reduction of greenhouse gas emissions through re-refining and energy recovery.
- SDG 9 (Industry, Innovation, and Infrastructure): Development of treatment facilities and digital monitoring platforms.
- SDG 11 (Sustainable Cities and Communities): Mitigation of soil and water contamination risks.
- SDG 17 (Partnerships for the Goals): Public–private collaboration for reverse logistics coordination.

G. Implementation Framework

A phased implementation strategy is proposed:

Phase 1: Regulatory strengthening, digital registry pilot, and national workshop mapping.

Phase 2: Infrastructure expansion, formalization of informal collectors, and IoT deployment.

Phase 3: Full national traceability system integration and expansion to additional hazardous automotive waste streams.

H. Model Contribution

The proposed strategic reverse logistics model extends beyond conceptual discussion by grounding its structure in field-based evidence from Panama's automotive sector . It adapts the best international practices to emerging-economy constraints characterized by fragmented infrastructure, partial regulatory compliance, and limited technological adoption.

By integrating infrastructure expansion, enforcement mechanisms, training initiatives, fiscal incentives, and digital traceability within a circular economy framework, the model provides an operational and scalable pathway to optimize ULO collection, treatment, and final disposal in Panama while strengthening environmental protection and industrial sustainability.

VI. Conclusions

The results demonstrate that the case study company has implemented a formal system for the collection of used lubricating oils (ULOs), including certified containers and authorized contractors, which represents progress compared to the informal practices still prevalent in many workshops and service centers in Panama. Staff awareness of environmental and health risks reflects an improved culture of responsibility, aligned with international trends in reverse logistics and circular economy principles.

Nevertheless, significant gaps remain. Regulatory compliance is perceived as incomplete, with limited knowledge of final disposal processes and insufficient transparency in traceability. The availability of specialized service providers is inadequate, restricting the frequency and reliability of collection services. These findings are consistent with regional experiences in Costa Rica, Colombia, and Mexico, where logistical and institutional barriers also limit the scaling of reverse logistics systems.

The conditional willingness of staff to participate in training highlights the need for flexible, practice-oriented programs that adapt to operational workloads. Respondents' recommendations for fiscal incentives and stronger enforcement align with successful measures applied in other Latin American countries, where tax benefits and regulatory oversight have increased participation in formal waste management systems.

This study confirms that reverse logistics provides a viable framework for improving ULO management in Panama's automotive sector. The case analyzed shows that formal practices can be effective, but their impact is constrained by gaps in infrastructure, enforcement, and incentives. The main contribution of this research is the proposal of a strategic reverse logistics model, grounded in circular economy principles, that addresses these barriers. By enhancing compliance, increasing provider capacity, and promoting stakeholder engagement, the model has the potential to transform ULO management into an opportunity for environmental protection, operational efficiency, and sustainable development.

The strategic reverse logistics model proposed in this study is structured around five key variables identified through expert interviews and survey results: infrastructure, regulation, training, economic incentives, and traceability. First, infrastructure refers to the availability of authorized service providers and certified collection systems, which must be expanded to ensure nationwide coverage and reliability. Second, regulation encompasses the enforcement of existing laws and the introduction of specific policies that strengthen compliance, supported by fiscal incentives to encourage participation. Third, training highlights the need for short, practice-oriented programs that adapt to operational workloads, ensuring that staff across workshops and service centers acquire technical knowledge and environmental awareness. Fourth, economic incentives are essential to motivate companies, particularly small workshops, to adopt responsible practices by reducing costs through tax deductions or municipal fee reductions. Finally, digital traceability integrates technological tools such as monitoring platforms and real-time registries to document collection volumes, dates, and disposal routes, thereby improving transparency and enabling audits. Together, these variables form a comprehensive framework that aligns with circular economy principles, transforming the management of used lubricating oils into an opportunity for environmental protection, operational efficiency, and sustainable development in Panama's automotive sector.

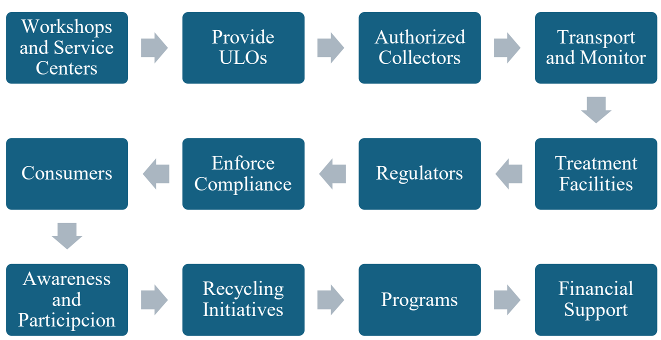

Fig. 2. Stakeholder Interaction Map.

VI. Recommendations

Based on the findings of this research, the following recommendations are proposed to strengthen reverse logistics for ULOs in Panama's automotive sector:

- Formalize Collection Networks: Establish agreements with authorized collectors to ensure frequent, reliable, and traceable recovery of ULOs across workshops and service centers.
- Capacity Building: Develop short, practice-oriented training programs on safe handling, regulatory compliance, and circular economy applications for industry personnel, adapted to operational workloads.
- Digital Traceability: Implement monitoring systems to record volumes, collection dates, and final disposal routes, enabling audits and improving regulatory oversight.
- Economic Incentives: Introduce fiscal benefits, such as tax deductions or reduced municipal fees, for companies that demonstrate proper ULO management through authorized channels.
- Awareness Campaigns: Promote environmental and health awareness among small workshops and customers to encourage adoption of responsible practices.
- Public–Private Collaboration: Strengthen cooperation between government institutions, industry associations, and service providers to expand infrastructure and ensure nationwide coverage.

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