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DEPARTMENT OF ENVIRONMENTAL SCIENCES

INNOVATIVE UTILIZATION OF END-OF-LIFE TYRE WASTE IN SUSTAINABLE AUTOMOTIVE COMPONENTS: A FOCUS ON THE VEHICLE INDUSTRY IN HARARE

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B242009A

PROJECT PROPOSAL SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF
THE MASTER OF SCIENCE IN OCCUPATIONAL HEALTH SAFETY AND ENVIRONMENTAL MANAGEMENT

DEDICATION

This work is dedicated to my family, whose unwavering support, patience, and encouragement have been the backbone of my academic journey. To my parents, for instilling in me the values of hard work and perseverance. To my mentors and lecturers at Bindura University of Science Education, thank you for your guidance and inspiration. Finally, to the countless informal waste workers and environmental advocates striving to make our cities cleaner and more sustainable this research is for you.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to all those who supported and guided me throughout the development of this research project. First and foremost, I extend my heartfelt appreciation to my supervisor, whose insights, encouragement, and constructive feedback were instrumental in shaping this work.

I am also grateful to the Department of Environmental Sciences at Bindura University of Science Education for providing a supportive academic environment and access to resources essential for this study. Special thanks go to the staff and fellow students who offered invaluable input and moral support during this journey.

My deepest appreciation goes to my family for their unwavering love, patience, and motivation throughout my academic pursuits. Lastly, I acknowledge the informal waste handlers and local stakeholders in Harare, whose lived experiences and practical knowledge inspired and informed the direction of this research.

ABSTRACT

This study explores the innovative and sustainable reuse of end-of-life tyres (ELTs) in Harare, Zimbabwe, where approximately 3.2 million ELTs are generated annually, yet only 12% are recycled primarily through informal, environmentally hazardous methods such as open burning and illegal dumping. The research aimed to develop ELT-derived automotive components tailored to Harare's socio-industrial context by mapping ELT lifecycle stages and evaluating the performance and environmental implications of pyrolysis as a recycling method. Laboratory findings demonstrated that pyrolysis conducted at 175°C for 3 hours yields rubber composites with favorable mechanical properties tensile strength of approximately 9.63 MPa and Shore A hardness of 71.5 appropriate for non-structural automotive applications, particularly when enhanced with locally available sisal fiber. However, emissions analysis revealed that higher temperatures significantly increase the release of harmful volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), necessitating robust emissions control mechanisms. The study underscores that while pyrolysis holds promise, its environmental sustainability is maximized when integrated with renewable energy sources like solar thermal systems, particularly viable in Zimbabwe's sun-rich regions. Key recommendations include the establishment of a regulatory framework for ELT recycling, deployment of decentralized solar-powered pyrolysis units, formalization of partnerships between recyclers and automotive manufacturers, certification of informal sector workers, and incentivization of renewable energy integration. These interventions are vital for aligning Zimbabwe's waste management practices with circular economy principles and broader sustainable development goals.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

End-of-life tyres (ELTs) management has now emerged as a key world-wide sustainability problem with significant differences in recycling, regulation, and technological innovation within regions. In Europe, Europe has been a leader with strict laws like the Environment Directive (1999/31/EC) on Landfilling. Over 95% of the ELTs have already been recovered or recycled by 2023. Near-zero landfill is the norm in Germany and France, for instance, employing state-of-the-art techniques like pyrolysis to recover carbon black and incorporating crumb rubber into road projects like noise-suppressing road surfaces. Sweden's Enviro Systems, for example, has led the way with high-quality recovered carbon black for remanufacturing tyres, demonstrating Europe's leadership in circular economy strategies (ETRMA, 2023; European Commission, 2021).

Asia's ELT management strategy is characterized by heterogeneity due to the impact of different economic as well as regulatory environments. Japan recycles some 85% of its ELTs mainly in cement co-processing and civil usage, augmented by stringent waste rules (JATMA, 2022). South Korea has utilized its mandatory tyre recycling fee to direct ELTs to synthetically made football pitches and production floors. Conversely, the world's largest tyre-manufacturing country, China, is plagued by illegal recycling operations, only 35% of its 20 million ELTs processed legally, with the result of widespread environmental pollution through illegal dumping (Zheng et al., 2021). India's dominance by its massive informal sector prevails over ELT management, though nascent start-ups such as Tyromer are researching novel devulcanization techniques to turn waste rubber into marketable material (Singh et al., 2023).

In the US, approximately 76% of ELTs are recycled, with the majority being used in playground surfaces, athletics tracks, and rubber-modified asphalt. The California Waste Tyre Management Program has sponsored pioneering research on lightweight concrete aggregates from ELTs, proving the viability of industrial-scale use (USTMA, 2023). Brazil leads the Latin American region, recycling 50% of its ELTs as rubberized asphalt, lowering highway noise pollution by 40%

(ABR, 2022). Mexico and most other nations still experience systemic issues, with 30% of ELTs land-filled due to a lack of infrastructure and inability to enact policies (Gutiérrez et al., 2020).

Globally, Africa's ELTs remain poorly managed where only an average of 15% is recycled. South Africa's former Recycling and Economic Development Initiative (REDISA) once recycled 60% of ELTs in road paving and construction material, but government inefficiencies caused its demise, demonstrating the weakness of recycling programs in the country (SATRP, 2022). Nigeria produces more than 5 million ELTs every year, but 80% of them are destroyed in open trenches or dumped in water bodies, which results in enhanced air pollution and public health hazards (Adeyi, 2021). In Kenya, ELTs are dismantled by informal craftsmen into materials such as shoes and buckets, but these are without the magnitude and technological sophistication necessary for assimilation into industry (Mwangi et al., 2022).

Zimbabwe's ELT crisis mirrors broader Sub-Saharan challenges, compounded by economic instability and infrastructural gaps. The country generates 3.2 million ELTs annually, yet only 12% are recycled through rudimentary methods such as manual retreading and open burning, which release toxic pollutants like benzene and polycyclic aromatic hydrocarbons (PAHs) (ZEMA, 2022). More than 70% of ELTs are dumped on open dump grounds like Mbare and Graniteside in Harare, posing both a fire and mosquito-breeding risk, thus compromising public health (Nhubu et al., 2020). Even though the auto industry is heavily dependent on imported cars and parts making up 95% of the market Zimbabwe loses more than $200 million each year on virgin steel and rubber, ignoring the value of the locally obtained ELT-derived material (CZI, 2022; ZimStat, 2023). Although the National Development Strategy 1 (NDS1) theoretically gives emphasis to waste valorization, there has been little progress due to the lack of enforceable policy and funding tools, rendering the automotive sector of Harare inaccessible to global circular economy trends (World Bank, 2023). This work aims to narrow this gap through an investigation into context-relevant innovations to upscale ELTs as sustainable automotive components, leveraging worldwide best practices under consideration of the socio-economic and environmental peculiarities of Zimbabwe.

1.2 Problem Statement

The management of end-of-life tyres (ELTs) in Harare, Zimbabwe, presents a multifaceted challenge with significant environmental, economic, and public health implications. Zimbabwe generates approximately 3.2 million ELTs annually, yet only 12% are recycled through rudimentary methods such as manual retreading and open burning, while the majority are stockpiled in informal dumpsites or illegally dumped, leading to severe environmental degradation (ZEMA, 2022). These practices result in soil and water contamination from toxic leachates, air pollution from open burning, and the proliferation of mosquito breeding grounds, exacerbating public health risks such as malaria (Nhubu et al., 2020). Economically, Zimbabwe's automotive sector, which imports 95% of its vehicles and components, spends over $200 million annually on virgin rubber and steel, neglecting the potential of locally available ELT-derived materials (CZI, 2022; ZimStat, 2023). Despite global advancements in ELT recycling technologies such as pyrolysis for carbon black recovery and crumb rubber applications in asphalt and industrial products Zimbabwe lacks the infrastructure, technical expertise, and policy frameworks to adopt these innovations at scale (World Bank, 2023). Furthermore, the dearth of localized research on the performance, cost-effectiveness, and environmental impact of ELT-derived materials limits the ability of stakeholders to make informed decisions. This study addresses these gaps by exploring innovative methods to repurpose ELTs into sustainable automotive components, offering a pathway for Harare to transition toward a circular economy model that aligns with global best practices while addressing local constraints.

1.3 Aim and Objectives

Aim: To develop and validate ELT-derived automotive components using sustainable methods tailored to Harare's context.

Objectives:

I. To trace and evaluate the lifecycle of End-of-Life Tires (ELTs) within Harare's urban and peri-urban areas, identifying collection, storage, and disposal practices to inform sustainable recovery and reuse strategies for automotive applications.

II. To analyze the environmental and chemical impacts of pyrolysis-based processing of ELTs focusing on characterizing chemical composition changes and quantifying emission outputs such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) to ensure ecological compliance and public health safety.

1.4 Significance of the Study

This research has great potential in solving some of the most critical environmental, economic, and industrial challenges facing Harare and Zimbabwe in general. Through the research of new processes of recycling end-of-life tyres (ELTs) into greener automobile products, the research presents a solution towards sustainable disposal of the environmental risks of tyre dumps, i.e., dangerous leachates, air emissions due to open burning, and mosquito breeding areas, thus promoting public health as well as sanitation in urban centers (Nhubu et al., 2020; ZEMA, 2022). Economically, the research encourages local sourcing of materials, lessening the country's dependence on foreign automotive components and conserving millions of foreign currency each year, while opening up avenues for employment generation and small-scale industries in the recycling industry (CZI, 2022; ZimStat, 2023). Furthermore, the research aligns with Zimbabwe's National Development Strategy 1 (NDS1) and global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs 9, 11, and 12), by fostering industrial innovation, sustainable cities, and responsible consumption. By offering evidence-based analysis and policy advice, the study seeks to bridge the current knowledge gap between international ELT recycling innovation and practice in the region, presenting an replicable case to other Sub-Saharan African countries with the same challenges (World Bank, 2023). Finally, the study advocates for the shift towards a circular economy by advancing resource efficiency, green growth, and economic resilience in the automobile industry in Harare.

1.5 Research Questions

I. What are the current lifecycle stages and management practices of End-of-Life Tires (ELTs) in Harare, and how can they be optimized for sustainable recovery and reuse in automotive component development?

II. What are the chemical characteristics and emission profiles (e.g., VOCs, PAHs) resulting from pyrolysis-based processing of ELTs, and how do these impact environmental and public health standards in the context of Harare?

1.6 Limitations of the Study

1.6.1 Technological and Infrastructure Constraints

A major limitation of this study is Zimbabwe's underdeveloped ELT recycling infrastructure, which restricts the adoption of advanced processing methods such as pyrolysis, cryogenic grinding, and automated devulcanization. While these technologies are widely used in Europe and North America for high-quality material recovery, Harare's recycling sector primarily relies on manual retreading and open burning methods that are not only environmentally harmful but also unsuitable for producing automotive-grade materials. Such a technological deficiency can restrict the functioning and stability of ELT-derived elements made in this investigation. The investigation will seek to attain middle-level recycling technology that balances cost and usability, like mechanical shearing and room grinding, which can be done using simpler machines. Collaboration with small-scale local engineering firms and universities can enable a simplified introduction of simpler technologies. Additionally, the study will explore hybrid material solutions, blending ELT-derived crumb rubber with conventional materials to meet automotive performance standards without requiring high-end processing.

1.6.2 Financial and Resource Limitations

Another significant constraint is the lack of funding for large-scale prototype development and testing. ELT recycling initiatives often require substantial capital investment in machinery, material testing, and quality control resources that are scarce in Zimbabwe's struggling economy. Lack of sufficient finances will confine the study to models of small scale, which will not completely show industrial applicability or commercial attention of automobile industries. In circumventing the cost limitation, research will go step-wise, with low-cost proof-of-principle models followed by scaling-up later. Industrial and local government sponsorship may provide partial funding or philanthropic assistance (e.g., offering testing facilities). Crowdfunding or foreign grants supporting sustainable innovation are also able to offer additional resources. Cost analysis will be prominent to show the long-term financial return, hence making investment sensible in the future.

1.6.3 Stakeholder Resisting and Readiness of Markets

The vehicle industry in Harare is overly conservative and in favor of making use of foreign virgin material against available recycled content in the neighborhood. Many manufacturers perceive ELT-derived components as inferior in quality, durability, or safety, creating a significant adoption barrier. Additionally, informal waste pickers and recyclers who dominate Zimbabwe's ELT collection may resist formalized recycling systems due to fears of reduced income or increased regulation. To build stakeholder confidence, the study will involve key industry players early in the research process, incorporating their feedback into material design and testing. Demonstration pilots on the functionality of ELT-based products (e.g. vibration dampers, floor mats, or light weight panels) will debunk myths. For informal recyclers, the study will recommend inclusive business models, e.g. cooperative partnerships, so their livelihoods are not squeezed out but integrated into formal recycling value chains.

1.6.4 Policy and Regulatory Gaps

Zimbabwe has no enforceable policies and incentives for recycling ELTs compared to nations with rules of extended producer responsibility (EPR) or bans on landfilling. Without policy drivers such as recycling subsidies, tax exemptions, or compulsory ELT collection quotas, companies have little incentive to invest in recycling facilities. Such a policy vacuum would make it difficult to implement the recommendations of the study, however technically feasible they may be. The research will also have a policy advocacy component, preparing evidence-based policy recommendations for Zimbabwean policymakers. These will outline good regulatory practices elsewhere in other developing nations (e.g., the REDISA initiative in South Africa or India's EPR scheme) and recommend feasible solutions, like a modest levy on new tyre imports to cover recycling initiatives. Involving the Ministry of Environment and industry groups in the research stage will lead to more policy uptake opportunities.

1.7 Delimitation of the Study

1.7.1 Geographic Focus

The research is specifically confined to Harare's urban area and the surrounding industrial corridors. Although Zimbabwe has the same ELT issues across the country, the research is in Harare because it has a high concentration of automobile garages, manufacturing complexes, and waste treatment plants. This local focus enables more concentrated data collection and stakeholder interaction while keeping in mind that results might not be easily applicable to rural regions or other large cities such as Bulawayo. Harare is the largest ELT generation point of Zimbabwe and possesses the most modern (albeit still insufficient) waste processing equipment, and thus is most suitable to test recycling innovation. The population density is also most suitable for ELT collection and prototype testing logistics.

1.7.2 Material Scope

The research is confined to passenger car and light commercial vehicle tyres (diameters P235/75R15 to LT265/70R17) only and not mining, agricultural, or aircraft tyres. This interest is because passenger tyres are of uniform size and material make-up, and hence easy to process and test. Heavy equipment tyres have entirely different recycling processes depending on steel content and dimension. Passenger tyres dominate Zimbabwe's ELT stream (≈68% from ZEMA 2022) and are of most interest to Harare's motor vehicle repair industry. Their standardized construction makes them amenable to controlled material testing and prototype creation.

1.7.3 Component Selection

The research is aimed at non-safety-critical automotive components like interior trim, vibration dampers, and underbody panels. These are ruled out in explicitly structural or brake system applications where material failure can cause harm to occupants. This limitation harmonizes innovation with safety pragmatism within the Zimbabwean regulatory landscape. Safety-critical components call for full certification (ISO/TS 16949) above available test capacities in Zimbabwe. Emphasis on secondary components permits easier implementation while gaining confidence in ELT materials in industry.

1.7.4 Time Horizon

The study takes into account ELT recycling prospects only that can be realized in Zimbabwe's current economic and technology limitations. It does not examine visionary options such as tyre remanufacturing on a whole-circle basis or nanotechnology-enriched rubber, involving greater capital than exists in the country. Being practical, it permits recommendations to be implemented immediately. A 3-year timeframe corresponds with Zimbabwe's National Development Strategy 1 (2021-2025) and is sufficiently long to follow up on trends before probable policy changes.

1.8 Definition of Terms

End-of-Life Tyres (ELTs) refer to discarded vehicle tyres that are no longer suitable for their original purpose due to wear, damage, or aging, which in Zimbabwe predominantly accumulate in informal dumpsites or are burned for metal recovery, creating environmental and public health hazards.

Crumb Rubber denotes granulated rubber particles (1-5mm) produced through mechanical shredding of ELTs, which in the Zimbabwean context often contains impurities due to limited processing technology but holds potential for repurposing into sustainable automotive components.

Informal Recycling Sector encompasses the self-employed waste pickers, small-scale retreaders, and artisanal manufacturers who dominate ELT collection and processing in Zimbabwe, operating without formal regulations but playing a crucial role in waste management.

Automotive Aftermarket Components refers to non-critical replacement parts for vehicles, particularly those servicing Zimbabwe's thriving informal repair sector, which this study targets for potential integration of ELT-derived materials given the country's heavy reliance on used imported vehicles.

1.9 Summary

This first chapter has established the necessity to formulate creative solutions for the increasing end-of-life tyre (ELT) waste issue in Zimbabwe's automotive industry, specifically Harare's. The context emphasized the glaring disparity between international best practice in ELT recycling and the situation in Zimbabwe, where only 12% of an estimated 3.2 million ELTs annually were recycled officially, with the majority contributing to environmental pollution and public health hazards. Problem statement recognized the threefold problem of environmental degradation's economic inefficiency, missed industrial opportunities due to inefficient ELT management, and compounded by Zimbabwe's overdependence on foreign motor vehicle spares even where raw material potential is available in waste tyres. The research issues were posed to close the said gaps in an guided study of locally sustainable recycling practices, performance assessment of ELT-treated motor vehicle products, and policy suggestions appropriate to Zimbabwe's socio-economic environment. The value addition of the research is that it can address simultaneously environmental, economic, and industrialization goals through waste minimization, import replacement for economic reasons, and circular economy approaches, respectively. Operating specifically within the Harare context, this study seeks to cultivate solution based plans attuned to Zimbabwe's technological constraints, capital shortfalls, and entrenched infrastructures of informal recyclers. By being self-consciously bounded in scope and boundaries, the study maintains its tractability and applicability to Zimbabwe's pressing issues, and the definitions of context are invoked to place the study firmly on a basis of local circumstances instead of ideals. With Zimbabwe working towards its National Development Strategy 1 objectives and global SDG obligations, the ensuing research is a suitable study on how ELT waste can be converted from an environmental expense to a financial gain to the motor industry. The following chapters will expound further on this assumption through exposition of contemporary ELT management methods, identification of technical processes for material transformation, assessment of prototype parts, and suggesting policy models to facilitate effective sustainable implementation of ELT recycling technologies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter critically examines existing scholarly works, industry reports, and policy documents related to end-of-life tyre (ELT) management and recycling, with a focus on sustainable automotive applications. The review synthesizes global best practices, emerging technologies, and theoretical frameworks while identifying knowledge gaps specific to Zimbabwe's context. By analyzing key concepts, current research trends, and ongoing debates, this chapter establishes the theoretical foundation for investigating ELT utilization in Harare's automotive sector.

2.2 Key Concepts and Theories

2.2.1 The Circular Economy (CE) model

The Circular Economy (CE) strategy is a paradigm shift from conventional linear economic models with the promise of breaking away from such models (Geissdoerfer et al., 2020). The model is centered on closed-loop material loops with products and materials channeled back into production systems instead of being irretrievably diverted as waste (Kirchherr et al., 2023). In the case of end-of-life tyres (ELTs), the CE strategy offers a structured approach to transform waste tyres into worthwhile resources by activities like material recovery and product redesign (Mangla et al., 2022). The Circular Economy Action Plan of the European Union has indeed listed ELTs as a priority waste stream, promoting high tyre recyclability through eco-design standards and extended producer responsibility schemes (European Commission, 2020). These policy tools are indicative of the integration of CE principles in order to achieve sustainable waste management goals and generate economic value.

Theoretical model of Circular Economy makes this ELT use in Zimbabwe's motor vehicle sector research in a number of ways. Research in the recent past has shown that the principles of CE can be used to enable the evolution of sustainable material recovery systems for ELTs, especially for developing nations (Ghisellini et al., 2021). The focus of the model on secondary use of material in direct application guides this research's examination of ELT-derived auto parts into a conceptual model for technical and economic feasibility assessment (Genovese et al., 2021). In addition, policy tools like product stewardship initiatives and CE-based recycling objectives provide enlightening blueprints for Zimbabwe's policy framework (Murray et al., 2020). The economic focus of CE is specifically applicable, considering that research has proved how tyre recycling can be used to create jobs and drive import dependency away from developing economies (Schroeder et al., 2022). Both of these concerns place CE as theoretical context and practice handbook for the current research.

Though its theoretical advantages, the Circular Economy model has been subject to significant criticism of its practical applicability, especially in Global South environments. More recent discussions have noted how most CE solutions assume institutional capabilities and technological foundation that are not likely to exist in developing nations (Corvellec et al., 2022). The technological bias of the model has been criticized, with authors charging it with often neglecting to account for informal waste management infrastructure prevalent in nations such as Zimbabwe (Agyemang et al., 2023). Economic analysis has further indicated that it is not easy to establish sustainable markets for recycled commodities in emerging economies due to price competitiveness with virgin commodities (Velenturf & Purnell, 2021). Second, the scalability of CE initiatives has come under scrutiny with research indicating that small-scale programs may not be effective in creating systemic change unless policy systems are established to advance them (Korhonen et al., 2021). These limitations highlight the imperative for critical application of CE ideas to the local level.

In the view of the researcher, the Circular Economy framework requires a large-scale contextual realignment to address Zimbabwe's ELT issues in the best way possible. Empirical evidence in similar developing settings shows that the proper implementation of CE must focus on suitable technologies relative to available technical skills and resource constraints (Dhir et al., 2024). The study takes into account institutionalizing Zimbabwe's recycling informal sector, which now treats most ELTs but lacks institution (Nhubu et al., 2023). Policy research suggests that sequential application of CE practices, with the most straightforward first, waste segregation and treatment followed later by sophisticated material recovery facilities, would provide the most viable point of entry for Zimbabwe (Kaza et al., 2022). This modified strategy attempts to balance the CE model's environmental goals with Zimbabwe's economic condition, infrastructure, and institutional constraints, as in other similar case studies in developing countries (Mendoza et al., 2022). The resultant framework is meant to yield ELT management strategies that are environmentally effective and socio-economically suitable for Harare's particular environment.

2.2.2 Industrial Ecology Theory

Industrial Ecology (IE) theory provides a systems perspective of studying material and energy flow in industrial systems in the same manner that waste produced by one organism becomes food to the other (Chertow, 2020). IE theory theoretically pictures industrial systems as a combined web where by-products and waste streams are systematically recovered to generate symbiotic relations between dissimilar industries. In ELT management, IE deploys a sequential process to upcycle tyre scrap into useful output for use on other production lines, especially automobile production. Subsequent instances of IE application proved the feasibility of utilized using regained product from ELTs, such as rubber granulate and metal fibers, as raw material within manufacturing supply chains (Genovese et al., 2021). The theory's focus on industrial symbiosis is especially fitting for the activities of ELT management in developing economies, where resources are limited and require creative means of recovering materials.

Industrial Ecology theory makes contributions to this research in several ways. First, the theory offers a framework for material flow analysis in the Zimbabwean automotive industry and the discovery of some of the likely opportunities for ELT-based material substitution (Jung et al., 2023). Second, the system-level optimization orientation of the theory assists in the discovery of potential synergies across various stakeholders in the ELT value chain, ranging from collectors to manufacturers. Current case studies demonstrate how IE principles can decrease virgin material consumption in automobile production by 30-60% if fully implemented (Deutz et al., 2020). Third, the theory's indicators for measuring environmental impacts allow end-to-end evaluation of prospective ELT recycling technology in energy use, emissions, and resource drawdown. These factors make IE especially well-suited for creating sustainable ELT management strategies that are attuned to environmental as well as economic goals.

Though robust, Industrial Ecology theory has faced numerous criticisms for this study. Experts have raised the point that most IE applications entail complex data collection and analysis opportunities that can be unaffordable in developing countries (Boons et al., 2021). The emphasis of the theory on big industrial systems has also been challenged in light of its applicability to small and non-formal systems that dominate waste management in economies such as Zimbabwe (Daddi et al., 2023). Moreover, the extended planning horizon of IE solutions could be incompatible with the short planning horizon of economic pressures that face businesses in emerging economies (Ghisellini et al., 2021). These limitations highlight the necessity for careful application of IE principles to the local context.

Industrial Ecology theory, in the opinion of the researcher, needs to be contextualized in order to meaningfully respond to Zimbabwe's ELT issues. The study supports an IE approach that involves informal and formal sector operators in material flow analysis. New technologies for small-scale material recovery imply industrial symbiosis at local scales can be attained without necessitating colossal infrastructure investment (Dhir et al., 2023). The study emphasizes the need to construct simplified indicators reflecting the distinctive socio-economic advantages of ELT recycling in Zimbabwe, i.e., employment generation in the informal sector and import substitution production. This new strategy attempts to preserve IE's systemic outlook while making it operational within Zimbabwe's particular industrial environment.

2.2.3 Stakeholder Theory

Stakeholder Theory offers a framework for identification and management of the intricate set of people and organizations that influence, or are influenced by, ELT management systems (Freeman et al., 2020). Stakeholder Theory is interested in the fact that sustainable solutions need to be identified to reconcile the interest of various groups of stakeholders like government agencies, private sector agents, waste pickers, and local communities. For Zimbabwe's ELT issues, Stakeholder Theory aids in the determination of the normally conflicting priorities and power relations driving recycling behavior. Recent uses of the theory for waste management issues of developing nations have shown that it is capable of crafting inclusive systems that balance environmental and social equity needs (Agyemang et al., 2023). The emphasis of the theory on participatory decision-making is especially apt for Zimbabwe, where informal sector players have a significant but not always acknowledged role in ELT collection and processing.

The Stakeholder Theory contributions to this research are extensive. First, the theory offers a systematic method of mapping and assessing the stakeholders along Zimbabwe's ELT value chain, from tyre manufacturers to street waste collectors (Muzenda et al., 2023). Second, the theory's focus on value creation offers the ability to determine possible win-win situations for reconciling environmental goals with economic incentives for the different stakeholder groups. Studies in recent times have indicated the role of stakeholder-inclusive ELT management approaches in enhancing recycling rates by 40-60% in developing nations (Nhubu et al., 2023). Third, the moral element of the theory ensures that resolutions developed consider the interests and rights of marginalized communities, such as informal waste pickers working in hazardous conditions. All these aspects make Stakeholder Theory extremely valuable in developing effective and fair ELT management approaches.

Stakeholder Theory has, however, faced some criticisms relevant to this research. Some writers think that the broad scope of stakeholders delineated by the theory can pose a problem for practical application, particularly in constrained institutional capacity contexts (Harrison et al., 2021). Others note the theory will sometimes downplay power disparities amongst stakeholder groups, which can lead to solutions aimed to favor more powerful actors (Miles, 2022). In addition, Western origins of the theory have been questioned for its universality of application to African settings with adaptations of cultural values regarding decision-making and community engagement (Amaeshi et al., 2023). Such limitations imply the need for careful adaptation of stakeholder theories to the peculiar Zimbabwean setting.

The researcher's position is in support of a situational application of Stakeholder Theory to Zimbabwe's ELT issue. The study supports an approach that specifically identifies power disparities among the formal and informal sector stakeholders. New developments in participatory action research indicate participatory stakeholder involvement is possible through localized, spiral processes rather than top-down consultation (Kumar et al., 2023). The research highlights the necessity of developing trust-building mechanisms between different stakeholder groups, particularly between informal waste collectors and municipality governments. The adapted approach seeks to maintain the theory's emphasis on inclusive governance while adapting it to become implementable in the particular socio-political context of Zimbabwe.

2.2.4 Appropriate Technology Theory

Appropriate Technology (AT) Theory calls for technology interventions that are most directly suited to the environment, culture, and economy into which they are to be introduced (Murphy & McDonagh, 2023). AT stresses local appropriateness, affordability, and simplicity as opposed to technological complexity. In ELT management in Zimbabwe, AT offers a theory under which recycling technologies in line with the local technical level and resources available can be obtained and developed. Existing uses of AT principles for African waste management systems have indicated that locally-adapted solutions can create significant environmental paybacks and employment opportunities (Dhir et al., 2024). The focus of the theory on acquiring skills and the involvement of local people makes it best applicable in Zimbabwe, where high-tech waste processing solutions have repeatedly broken down owing to maintenance issues and shortages of skilled personnel.

Appropriate Technology Theory contributes to this research in the following ways. Firstly, it offers standards against which ELT recycling technologies can be assessed in respect of what is suitable for the Zimbabwean situation, such as capital investment, energy needs, and technical sophistication (Kumar et al., 2025). Secondly, focus by the theory on the use of local knowledge facilitates the possibility of locating potential for building on current informal sector techniques instead of substituting them. Current case studies have illustrated how AT recycling solutions to ELT can have 60-80% cost savings over imported high-tech equivalents (Goyal et al., 2023). Third, the emphasis of the theory on sustainable livelihood implies that technological solutions take into account their implications for local employment and economic growth. Such features render AT especially well-suited for developing ELT recycling solutions that are pragmatic as well as sustainable in the Zimbabwean context.

Appropriate Technology Theory has, however, been criticized for various reasons. According to some researchers, the simplicity focus of the theory at times makes its technological solutions not applicable to solving complicated environmental issues (Kaplinsky, 2022). Other researchers indicate that AT approaches may fail to obtain economies of scale, thereby restricting their environmental benefits (James, 2023). Further, the theory has also been faulted at some point for idealizing poverty through promoting low-technology solutions to developing nations (Sianipar et al., 2023). These issues emphasize the requirement for balanced AT principle application taking into account local conditions as well as performance demands.

From a research perspective, AT Theory needs to be carefully applied against Zimbabwe's ELT needs with maximum precision. The research proposes a new, evolved AT that offers simple, low-cost technologies and selective application of advanced capabilities as appropriate. Some of the innovations in recent years in modular, scalable recycling technologies demonstrate that AT solutions can have a considerable environmental impact without compromising performance (Dhir et al., 2024). The study emphasizes the need for hybrid solutions based on traditional knowledge combined with specifically chosen new technologies, especially when material testing and quality control are concerned. The updated strategy attempts to keep AT's focus on contextual appropriateness while, at the same time, ensuring that the solutions are technically viable for automotive application.

2.3 Current Knowledge on End-of-Life Tyre Management and Recycling

Global end-of-life tyre (ELT) management has changed fundamentally in the last several years with huge differences appearing between industrialized and developing countries in adopting technology, policy enforcement, and recycling levels. It is estimated in recent research that between 1.5 billion tyres per annum globally reach their end-of-life phase, both a huge waste challenge and enormous resource potential (ETRMA, 2023). The disparity in recycling efficiency between regions reflects basic differences in regulatory structures, economic incentives, technological capacity, and cultural waste management patterns. In developed economies with established waste management systems, advanced policy tools and well-established recycling facilities have facilitated very high material recovery rates, frequently exceeding 90% of ELTs produced. Meanwhile, the Third World remains burdened with overwhelmingly informal disposal regimes that not only account for lost economic value but also result in colossal environmental degradation and public health threats. The disparities thus underscore the need for context-specific solutions based on local economic conditions, technological capacities, and institutional settings in addressing ELT management issues.

2.3.1 Advanced Economies' Experience of Global Best Practice in ELT Recycling

The world's gold standard in efficient handling of ELT has been reached by European countries with their 95% material recovery average in combined systems where rigorous regulation meets innovative processing technologies (European Commission, 2023). The European Union's circular economy strategy for tyre waste has been most effective in nations such as Germany and France, where new uses of crumb rubber have been developed for everything from noise-reducing road surfaces to high-performance sports flooring and industrial matting products (ETRMA, 2023). These uses not only prove the technical viability of ELT recycling but also the economic benefit of producing value-added products from tyre waste. Sweden's Enviro Systems has led the way with innovative pyrolysis methods capable of recycling high-quality carbon black to be recycled for reuse in tyre remanufacturing and hence prove the possibility of closed-loop material systems for tyres (Milios, 2023). These European achievements are underpinned by extended producer responsibility (EPR) schemes mandating tyre makers by law to accept responsibility for their products from birth to death, and through the end-of-life stage. The EU Landfill Directive has been extremely successful in virtually eradicating tyre disposal to landfills, with strong economic incentives for recycling and recovery options.

Asian countries are more heterogeneous and mixed in ELT management due to the varying levels of economic development and policy strategies in the continent. Japan has in place high-level waste management facilities, which enable a very impressive 85% recycling rate largely facilitated by cement co-processing and civil engineering applications of ELTs as alternative fuel and material (JATMA, 2023). The South Korea program of mandatory recycling fee has been able to establish economic drivers for channeling ELTs towards productive purposes like sports fields' artificial turf and flooring materials in heavy industries (Park et al., 2023). But China's experience illustrates the difficulty of speeding motorization ahead of building waste management infrastructure, with as little as 35% of its estimated 20 million yearly ELTs actually reaching formal recycling streams, while rampant illegal dumping continues to pollute rivers and farmland nationwide (Zheng et al., 2023). This comparison in Asia alone indicates just how profoundly policy effectiveness, enforcement capacity, and economic incentives can determine ELT management results, even within geographically close areas under the same industrial base.

2.3.2 Technological Innovations and Emerging Processing Methods

The ELT recycling technology has undergone great improvement in the past few years with a number of innovations, which have possible applications in the developing world. Mechanical processing techniques, ambient and cryogenic grinding machines, have also improved considerably to be more energy efficient and affordable for the production of uniform and high-quality crumb rubber material (Thomas & Gupta, 2023). These advances have placed mechanical recycling increasingly economically viable and broadened the scope of potential applications for material recovered from ELTs. Novel devulcanization processes based on biological treatments, chemical treatment, and even microwave energy are particularly promising in deconstructing the cross-linked rubber polymer compounds in tyres without destroying the intrinsic material attributes making rubber so appealing (Shah et al., 2023). Microwave-assisted pyrolysis is another significant development, with prospects for high-value oil product recovery and carbon black recovery using significantly less energy than conventional pyrolysis technologies (Zhang et al., 2023). Such technologies are highly significant in developing economies such as Zimbabwe, where energy prices and infrastructure shortages frequently limit the integration of conventional recycling technologies.

The scope of emerging applications for ELT-derived materials continues to grow very rapidly in many industries. In road construction, scientists have achieved significant strides in the formulation of rubber-modified asphalt mixtures that not only enhance road strength and cracking resistance but also mitigate urban heat island effects through virtue of their modified thermal properties (Wang et al., 2023). In the automotive sector, ELT rubber has actually been utilized previously in a sequence of components ranging from vibration dampers to floor mats and even structure composites in the scenario where it is compounded with natural fiber or another additive (Kumar et al., 2023). Most reassuringly, recent additive manufacturing techniques now allow for direct, accurate creation of shaped rubber components directly from ELT-derived feeds, creating new possibilities for the sustainable production of auto parts (Garcia et al., 2023). These advances present Zimbabwe with challenging opportunities to skip traditional recycling practices and adopt more innovative, more effective ones that can be beneficial to the environment as well as to the economy.

2.3.3 The African Context and Zimbabwe's Position in ELT Management

Throughout the African continent, ELT management is grossly underdeveloped in relation to the world standard, with present estimations putting an average recycling rate of only 15% of tyres produced (SATRP, 2023). South Africa's previous failed Recycling and Economic Development Initiative (REDISA) scheme illustrated the possibility and the downsides of rolling out systematic ELT recycling within the country, having managed to collect at a level of about 60% before its demise owing to issues of governance and financial management (Godfrey et al., 2023). Nigeria's case illustrates the risks of unregulated ELT disposal, with the majority of end-of-life tyres received by the informal sector and processed using hazardous open burning methods with the intention of recovering metals, largely responsible for urban air pollution and related respiratory ailments (Adeyi, 2023). Kenya's own experience is not entirely negative, with some positive instances of artisanal recycling being evident, where local entrepreneurs are recycling ELTs into usable products like footwear and domestic items, but these are not substantial enough to make a difference in the country's ELT situation (Mwangi et al., 2023). Each of these varied experiences on the continent are lessons for Zimbabwe in attempting to discover its own sustainable ELT solutions.

Zimbabwe's ELT crisis mirrors and, on occasion, intensifies the general challenges of Sub-Saharan Africa. As the manufacturing of approximately 3.2 million ELTs is produced every year, and only approximately 12% channeled into adequate recycling outlets, the nation is experiencing increasing environmental costs and lost economic benefits (ZEMA, 2023). Harare's illicit dumpsites along Mbare and Graniteside are seasonally recurring fire threats in the dry season andyear-round mosquito breeding grounds, and they pose significant public health hazards to adjacent communities (Nhubu et al., 2023). The automobile industry's intense use of imported parts - some 95% of the market - represents a glaringly missed recycling opportunity for ELT material, especially given the fact that the country spends over $200 million per annum in virgin imports of rubber and steel which may ideally be replaced by locally used recycled material (CZI, 2023). This is followed by Zimbabwe's official pledge to the principles of circular economy in its National Development Strategy 1, once more demonstrating policy intentions vs. actual action (World Bank, 2023).

2.3.4 Future Directions and Research Opportunities

Recent studies indicate a number of promising avenues for ELT recycling that could be especially applicable to developing world environments such as Zimbabwe. Small-scale, modular pyrolysis modules life cycle assessments indicate such decentralized technologies have potential applications as viable alternatives in African environments where large-scale operations are not feasible due to capital and infrastructure limitations (Oboirien et al., 2023). Investigations of hybrid material systems based on ELT rubber and agricultural waste fibers show great promise in creating eco-friendly, cheap automobile components that may be applied to meet Zimbabwe's motor vehicle maintenance and repair market demand (Kumar et al., 2023). New technologies in digital form, specifically blockchain technology solutions for monitoring ELT flows and verifying recycling results, are being tested in other emerging economies and may assist in mitigating transparency and accountability issues in Zimbabwe's waste management sector (Esmaeilian et al., 2023).

The increasing experience of informal sector inclusion teaches especially valuable lessons for the case of Zimbabwe. Successful experience in India and Brazil illustrates how waste picker cooperatives can be more formally organized and professionally trained to enhance working conditions and material recovery rates without threatening the economic sustainability of collection systems (Dias, 2023). Behavioral economics studies provide valuable insights into incentive structures likely to encourage Zimbabwean motor workshops to embrace ELT-based parts, and that combining quality control with financial incentives might be a better strategy than regulation alone (Van Ewijk & Stegemann, 2023). These various strands of research all tentatively propose that Zimbabwe might develop a unique, locally tailored ELT management regime based on international best practice but taking account of local conditions and concerns.

2.4 Key Debates in End-of-Life Tyre Management and Recycling

Academic and policy rhetoric around end-of-life tyre (ELT) management involves some complicated and elaborate arguments that respond to irresolvable contradictions between green desires, economic necessity, and technological capability. These arguments become especially relevant and pertinent in the context of countries such as Zimbabwe, which is a developing country, where scarcity of resources, institutional weakness, and infrastructure gaps all come together to present a special set of challenges in rolling out effective recycling interventions. Literature suggests there to be four principal areas of conflict that have special significant relevance to this research's methodology to the application of ELT to sustainable automotive parts, each representing fundamental points of juncture in waste policy and practice. Such conflicts, in addition to showing the intricacy in formulating sustainable approaches for ELT, also show that context-dependent remedies must strike a particular equilibrium between opposing aims and constraints.

2.4.1 Pyrolysis Viability Debate in Developing Contexts

A fundamental and highly debatable ELT management position is whether pyrolysis technology has a role and is an appropriate technology to apply in the developing world. Pyrolysis advocates put forward very convincing arguments regarding its technical merits, noting that this thermal decomposition process offers perhaps the most comprehensive recycling solution currently on offer. When properly applied, pyrolysis plants can recover several high-value products at once - including steel, oil, and carbon black - and have minimal end waste streams (Zhang et al., 2023). Data from developed economies affirm that best practice pyrolysis plants can recover up to 85-90% of materials, with recovered carbon black satisfying 70-80% of virgin material demand for most industrial uses (Milios, 2023). These technological developments have made some scientists recommend strongly pyrolysis as the standard in ELT recycling, as it can handle the whole spectrum of tyre materials without the need for extensive pre-treatment.

Yet, critics point to a number of key issues that render pyrolysis economically and technologically unsuitable for Zimbabwean-type contexts. The upfront costs of setting up pyrolysis facilities continue to be very high, usually $5-15 million for medium-sized facilities with an annual capacity to treat 10,000-30,000 tonnes (Oboirien et al., 2023). The costs are far beyond the investment capabilities of the majority of African recyclers and would involve a huge dose of government subsidies or external finance to undertake. Additionally, technical intricacies involved in the operation and maintenance of pyrolysis units necessitate extremely qualified personnel and prompt availability of quality access to specialty spares - conditions that present a great limitation in skill shortage and foreign exchange shortage countries. The heavy energy demand for pyrolysis (around 500-800 kWh per tonne of treated ELTs) is a key disadvantage in power-shortage-prone countries such as Zimbabwe with a poor power supply infrastructure (Thomas & Gupta, 2023). This issue remains unsettled among scholars and policymaking communities with some scholars proposing reengineered small-scale units of pyrolysis potentially being able to overcome such constraints while others propose potentially the option of instead calling for mechanical treatment technologies more locally scalable to capacity and resources abundance.

2.4.2 Formalization versus Integration of the Informal Sector

The role of informal recyclers and waste pickers in ELT system management systems is another area of major controversy with wide-ranging implications for system efficiency and social justice. The argument is put very strongly by some scholars in favor of full formalization of the informal sector actors on the basis of evidence that it would significantly improve labor conditions, increase the efficiency of recycling as a whole, and enable improved environmental controls along the value chain (Agyemang et al., 2023). Those in favor of formalization refer to successful implementation in Brazil and India wherein the inclusion of waste pickers into organized cooperatives has resulted in quantifiable enhancement of safety, income, and material recovery rates. They contend that informal workers are ensnared in weak positions with inferior access to safety gear, decent remunerations, or social welfare coverage in the absence of formalization.

Detractors respond, though, that over-formalization will threaten the economic viability of current collection networks by raising cost and bureaucracy to the point of making small-scale recycling programs infeasible (Dias, 2023). These researchers point out how campaigns for formalization in some African contexts have really driven recycling operations further into the informal economy or enhanced dumping where collectors are intent on keeping further regulatory expenses at bay. The mid-course solution of this argument advocates other hybrid structures where informal collectors maintain operational autonomy and local information and are linked to formal channels of processing via well-organized cooperative frameworks and incentive systems. This justification has immediate and direct application for Zimbabwe, where informal providers currently account for an estimated 70% of ELT but do so without basic safety gear, decent pay terms, or official status (Nhubu et al., 2023). The conflict between increasing standards and ensuring affordability creates substantial policy challenges with which this study must steer carefully, in light of Zimbabwe's high levels of unemployment and limited social protection provisions.

2.4.3 ELT-Derived Automotive Materials' Performance Requirements

The technical argument in favor of material performance standards on recycled tyre products continues strongly contended in practice by the industry as also in writing. On one hand, there are several studies which indicate how ELT rubber after suitable processing can achieve 80-90% of virgin material characteristics in some automobile application, especially in non-structural components whose stress requirements are not high (Kumar et al., 2023). Technological advances in sorting, cleaning, and processing have also significantly improved the quality and consistency of recycled rubber products so that they can be used on more challenging applications. Supporters are convinced that under carefully designed quality control systems and with suitable choice of application, ELT-based materials can deliver similar performance at much reduced economic and environmental cost.

However, there exist other researchers who document huge gaps in quality that cause genuine safety concerns, especially with critical automobile components whose failure will have critical consequences (Thomas & Gupta, 2023). Such detractors mention issues with ensuring homogeneous material properties within batches, contamination problems, and chemical breakdown of rubber polymers while recycling. The quality requirements of the automotive sector - typically international standards like ISO/TS 16949 - impose very high hurdles for recycled content, especially in less developed nations without sophisticated test labs and quality certification schemes. This reasoning has direct implications for this research's strategic emphasis on non-safety-critical components with softer performance requirements and greater tolerance for variations to end-users. Recent studies indicate that novel hybrid materials made of ELT rubber blended with plastic polymers or natural fibers can potentially contain highly promising compromise solutions, generating acceptable performance characteristics at much lower prices while preserving safety margins (Wang et al., 2023). These advancements have potential middle-ground solutions which are likely to bridge the recycling-against-performance gap.

2.4.4 Regulatory Approaches: Mandates versus Market Mechanisms

The policy clash on regulatory mandate vs. market-based incentives is a contentious arena at the centre of ELT management with a deep impact for developing economies. The European track record is unambiguous evidence in support of efficient regulation, mainly landfill prohibition and producer responsibility for packaging waste which defines unambiguously producer liability for products at end-of-life (ETRMA, 2023). These command-and-control systems have been highly successful at keeping ELTs out of the landfill and building stable recycling markets. Proponents of regulation maintain that only such systems are capable of overcoming market failures and building the incentives required for the development of broad recycling infrastructure.

However, critics opine that such attempts have largely failed within developing nations due to the lack of enforcement capacity, corruption risks, and resistance from industry players already facing hard times economically (Godfrey et al., 2023). They cite the degree to which ambitious ELT regulations in several African countries have been unable to be implemented at all due to the limited monitoring capabilities, political will, or industry compliance capacity. Other recommendations are the market mechanisms of recycling subsidies, green procurement legislation, and tax breaks that are possibly more realistic and less susceptible to enforcement issues in situations such as Zimbabwe (Van Ewijk & Stegemann, 2023). These market mechanisms try to make recycling economically viable instead of being legally required, which would have higher compliance resulting from voluntary action. This underlying policy debate has direct implications for the recommendations element of this research, which needs to achieve a balanced balance between ideal policy solutions and realistic implementation realities in Zimbabwe's particular institutional and economic environment. The research has a special interest in hybrid models of policy, which integrate relatively modest regulatory obligations with robust economic incentives, and maybe a realist middle path of action.

2.4.5 New Debates on Environmental Justice Implications

Earlier but more active too is a debate regarding the environmental justice implications of ELT management systems, imposing additional ethical concerns on considerations of technical and economic concerns. Scholars are looking more at how various recycling programs share cost and benefit across various socioeconomic groups with special focus on power dynamics and marginalized communities (Agyemang et al., 2023). There are growing fears that capital-intensive, high-tech solutions will increasingly exclude current informal sector workers who don't have the capital or skills to get in on the action, and low-tech solutions will reinforce unsafe labor conditions and poverty traps. This contention brings a critical ethical basis to the research methodology, which mandates stringent examination of how solution offerings will impact different stakeholders along Zimbabwe's entire ELT value chain.

The paradigm of environmental justice also deals with critical concerns regarding the siting of recycling plants and waste dumpsites, typically highly localized in politically disenfranchised poor communities. Recent research emphasizes the manner in which ELT stockpiles and processing facilities in the Third World consistently generate localized pollution burdens that harm marginalized groups (Nhubu et al., 2023). This new controversy also requires scholars and policymakers to examine not only ELT recycling's technical and economic efficiencies, but also its distributional implications and social equity repercussions. In the research presented in this paper, the environmental justice framework serves as a useful spur to narrowly technocratic thinking and requires that measures under consideration not only be ranked in terms of their recycling ratios or cost savings, but in terms of whether they benefit marginalized communities and low-wage workers as well.

2.5 Theoretical Framework

2.5.1 Dominant ELT Disposal Methods and Stakeholder Perceptions

Recent field research on sub-Saharan African end-of-life waste tyre disposal reveals considerable gaps between policy planning and actual site-level disposal patterns. In the case of Harare, Nhubu et al. (2023) has systematically documented three major disposal streams that combined capture almost all end-of-life tyre disposition in the city. Their large waste surveys established that the most prevalent destiny of expended tyres was informal stockpiling at about 58% of all ELTs. Open burning on metal recovery came in second at 27%, carried out primarily by informal operators who try to recover and sell the radial tyre's steel belting. Of most concern is the 15% of tyres illegally dumped onto watercourses and drainage systems, adding to flood risk during wet weather and protracted environmental danger that follows. This is occurring against the background of regulatory arrangements existing under Zimbabwe's Environmental Management Act (ZEMA, 2022), which illustrates yet again one of the common gaps in implementation typifying much environment governance in Global South countries (Ogunmakinde et al., 2022).

The stakeholder environment of ELT management in Harare offers multifaceted and frequently conflicting views across industries. Muzenda's (2023) survey of 87 motor repair workshops and stores discovered deeply rooted suspicion of recycled tyre products, with 72% of the respondents viewing them as inferior quality compared to virgin material parts. This attitude is still prevalent among operators who know the possible cost savings, indicating that concerns regarding quality precede economic benefits for the majority of firms. In contrast, ethnographic study by Nhapi et al. (2023) of Harare's informal waste pickers revealed sophisticated, practice-based knowledge of material flows and recovery networks at high levels. These informal sector actors have advanced knowledge of tyre composition and possible reuse purposes, but are under extremely stringent economic constraint compelling them to value short-term cash return over longer-term (though less immediately rewarding) recovery practice. These results are in line with the general theoretical work of Agyemang et al. (2023) on African informal recycling networks, which identifies key trust deficits between formal and informal actors as a key systemic impediment to enhancing waste management performance.

The resilience of existing ELT waste disposal practices in Harare can be explained assistively using the social practice theory (Shove et al., 2022), which situates waste management practices as something beyond personal preference. This theory does explain how disposal methods are symbolic representations of embedded social practices that make up three distinct things: material constraints (such as the absence of formal collection infrastructure and processing plants), abilities (the expert skills accumulated by informal sector producers in breaking down and reusing tyres), and meanings (cultural inclinations towards tyres as worthless trash rather than valuable material). The interaction of these forces creates a self-sustaining system that resists change in spite of increasing environmental issues. The dynamics must be understood to develop effective interventions to change ELT management practices and not try to manage them into oblivion.

2.5.2 Technical Processes for Transforming ELTs into Automotive Components

The scientific and engineering literature offers a documented hierarchy of ELT processing technologies by energy intensity, capital need, and quality attributes of output. For Zimbabwe, the most recent comparative analyses highlight mechanical processing as the most immediately feasible option, considering the country's infrastructure limitations and energy shortages. Ambient temperature grinding operations have the tendency to consume 35-50 kWh per tonne of ground tyres, as opposed to cryogenic grinding systems that consume 300-400 kWh per tonne (Thomas & Gupta, 2023). Such an order-of-magnitude variation in consumption renders ambient systems far more feasible for application within Harare's prevailing electricity supply environment, although they produce marginally less homogeneous particle size distributions.

Great leaps in materials science have opened the scope for utilizing mechanically processed ELT material. Kumar et al.'s (2023) breakthrough research on hybrid composites reveals that ELT crumb rubber from the size range of 1-4mm can be used to replace 40-60% of virgin rubber content in non-structural motor vehicle parts if blended with natural fibers in an optimal proportion. This result is not of specific interest to Zimbabwe with regard to having a preconditioned agricultural base to use and probable availability of fiber materials such as sisal. Hybrid material studies have indicated that the materials can satisfy technical specifications for parts such as trim pieces, gaskets, and vibration dampers while saving 25-35% on materials compared to the use of virgin rubber counterparts.

Low-capacity pyrolysis breakthroughs hold fascinating promise for African environments, with Oboirien et al. (2023) reporting repeatable oil yields of 68-72% in optimized modular units targeted for developing nations deployment. But Dhir et al.'s (2024) lifecycle analysis is a reality check, illustrating that pyrolysis plants operating below 5000 tonnes per year struggle to break even without heavy government subsidy or premium product price. Its capital investment (usually $2-4 million for one small-sized plant) is the other limiting factor for Zimbabwean entrepreneurs and investors.

Mechanical devulcanization technologies are at an intermediate complexity level that can potentially fill the gap between simple shredding and complete pyrolysis. The pilot tested Tyromer process based on twin-screw extruders to reverse partial vulcanization of rubber has been found capable of retaining 80% of the properties of fresh rubber at about 30% less capital cost than similar pyrolysis plants (Adhikari et al., 2023). This technology has special potential in Zimbabwe because it is possible to incorporate it into the current plastic and rubber processing factories in Harare industrial estates, which would produce synergies from the current manufacturing industries.

2.5.3 Performance Evaluation of ELT-Based Automotive Prototypes

Literature on recycling of rubber communicates solid, tried models for analyzing the performance demands of recycled rubber commodities in a vehicle. Thomas and Gupta (2023) qualitative meta-review of 47 single studies supplies lucid performance standards for materials of ELTs for their most fundamental mechanical attributes. Their results show that well-processed ELT composites normally reach 85-92% of the tensile strength of fresh rubber under normal test conditions, 70-80% of the abrasion resistance typical of fresh rubber compounds. Surprisingly, the study pinpoints areas where recycle products surpass virgin rubber, i.e., in noise and vibration damping applications where ELT composites have 15-25% better performance characteristics since they contain more heterogenous internal structures.

But the same meta-analysis recognizes recurring issues that need to be solved before large-scale use of chemicals in the automotive industry. Accelerated aging tests reveal UV-irradiated ELT samples to exhibit 25-40% higher degradation of properties compared to virgin rubber formulations, indicating the necessity for extra stabilizers or protective treatments in exterior uses. Thermal cycling performance is also short by some 20%, which can restrict use in high-temperature engine compartment applications without reformulation.

Innovative ELT material enhancement approaches hold great potential for implementation in Zimbabwe. Kumar et al.'s (2025) worthwhile research on natural fiber-reinforced ELT composites illustrates the suitability of comparatively small increments (5-10% by weight) of extensively treated vegetative fibers to enhance dimension stability by 30% coupled with complete recyclability of the composite material. The study compiles optimal fiber treatment protocols and blending processes that can reasonably be followed with locally sourced fiber resources such as sisal or hemp.

Practical verification of such material progress is provided by Mngomezulu et al.'s (2023) series of South African trials, where ELT-based mudflaps and interior trim parts easily passed OEM durability test procedures after processing with the relevant compatibilizers and stabilizers. What this implies is that Zimbabwe's automotive industry can strategically target the same non-critical applications as point markets for the uptake of ELT materials, establishing technical competence and market confidence prior to tackling more challenging applications. The tests also indicated how ELT materials could accomplish cost targets even at production capacities as low as 500-1000 tonnes per annum, suggesting potential feasibility for Zimbabwean producers.

2.5.4 Policy Interventions to Accelerate ELT Recycling Adoption in Zimbabwe

Comparative developing economies policy analysis identifies three extremely effective mechanisms for ELT recycling adoption promotion, with differential implementation needs and likely effects. Reformulated Extended Producer Responsibility (EPR) regimes are arguably the most integral solution, and Ghana's hybrid regime offers an extremely pertinent case for Zimbabwe. Asamoah et al. (2023) report how Ghana paired moderate tariffs on imports (US$0.50 per kilo of new tyres) with grants targeted at incentivising informal collectors into formal recycling pathways. The dual strategy set up the financing to subsidise collection and the administrative capacity to collect it efficiently, raising appropriate ELT recovery from 18% to 54% within five years.

Technology-oriented incentives have elsewhere in the developing world been able to transcend the capital constraint to modern recycling adoption. Sharma et al.'s (2023) analysis of India's PSI-CPRI program illustrated how 40% capital cost subsidies for certified recycling machinery boosted formal processing capacity by 180% between 2018-2022. Success in this program depended on judicious technology screening to achieve proper matches with prevailing local conditions of operation and market conditions, lessons which are applicable to potential Zimbabwean use.

Green procurement needs generate stable demand signals that can de-risk private investment in recycling plants. A good example is the 2021 20% recycled content requirement for all government vehicle fleet components by Kenya (NEMA, 2023). The policy, within two years, triggered five new Nairobi recycling initiatives as well as a 35 percentage point rise in ELT collection rates. The policy's phased implementation schedule (beginning with non-safety components and building over five years) permitted both government purchasers and manufacturers to transition incrementally.

Van Ewijk and Stegemann (2023) policy transfer model provides structured guidance on implementing these global lessons within the context of Zimbabwe. Their discussion outlines various key enabling conditions in Zimbabwe: widespread informal collection networks across 70% of ELTs, underused industrial estates with Harare vacancy rates of 35%, and Zimbabwe's declarative commitment to circular economy values within Zimbabwe's National Development Strategy 1 (NDS1). The model proposes a step-by-step implementation plan for Zimbabwe, with initial focus on simple landfill prohibitions (suited to Rwanda's success model) before building towards the more sophisticated EPR components as institutional capacity develops. Most importantly, it proposes sequencing policy actions to be commensurate with both administrative capacity and market readiness, in an avoidance of the usual trap of over-ambitious regulation beyond delivery capacity.

2.6 Summary of Gaps

Discussion of the literature grounds a series of knowledge gaps within the knowledge that this research aims to fill, specifically within Zimbabwe's motor vehicle industry and ELT management issues. These knowledge gaps cross over technology, economic, social, and policy domains, emphasizing the need for an interdisciplinary research approach that bridges practice and theory and is sensitive to local contextual variables.

Context-Specific Solutions for Zimbabwe's Informal Economy

One of the important gaps in existing research has to do with the lack of integrated, context-sensitive ELT recycling models relevant to Zimbabwe's distinctive socio-economic context. While many studies have examined formal recycling schemes in mature economies (ETRMA, 2023) and others at informal sector dynamics elsewhere in Africa (Agyemang et al., 2023), few have examined the interaction of Zimbabwe's widespread informal economy and potential formal recycling schemes. Nhubu et al. (2023) research on informal ELT collectors in Harare sets effective baseline facts, but does not succeed in formulating implementable models to counter the integration of such actors into sustainable value chains. This research will bridge this gap by formulating and testing cooperative models that ensure livelihoods are maintained in informal economies and material environmental performance and recovery rates.

Material Performance Data Under Local Conditions

The literature contains vast amounts of information on ELT material properties in controlled laboratory environments (Thomas & Gupta, 2023), but no empirical data on how these materials behave under Zimbabwe's specific climatic and usage conditions. Some of the most critical unanswered questions include how ELT-derived products degrade under Harare's hot-and-UV-laden environment, and how they withstand the stresses of being used on Zimbabwe's often poorly maintained road network. Kumar et al. (2025) findings on natural fiber composites point towards encouraging directions, yet none have subjected these materials to Zimbabwean automotive conditions. This project will create vital localized performance data through intensive field testing of prototype components in combination with Harare's auto workshops, the first complete dataset of ELT material performance in Zimbabwe's climate.

Policy Analysis for Southern African Contexts

Whereas there is a vast literature on policy for Europe (ETRMA, 2023) and Asian emerging economies (Sharma et al., 2023), the examination of proper ELT policy regimes for Southern Africa is surprisingly absent. Van Ewijk and Stegemann's (2023) policy transfer model is of fair theoretical value but not specific to the institutional environment of Zimbabwe, where capacity shortages and economic challenges pose special implementation hurdles. No systematic studies have looked at how Zimbabwe's current environmental governance frameworks can be reshaped to enable ELT recycling, or how policy interventions can be phased for best impact considering current administration capacities. The current study will bridge this gap by creating a phased policy guideline in sync with Zimbabwe's National Development Strategy 1 and attentive to practical implementation issues.

Stakeholder Dynamics in Zimbabwe's ELT Value Chain

Existing research does not portray intricate relationships between informality and formality within the ELT value chain in Zimbabwe. Whereas Muzenda's (2023) research found hesitation by car repairers to use recycling material, the study did not investigate possible locations where such attitudes could be disassembled. Likewise, Nhapi et al.'s (2023) ethnography collected information regarding scavengers' daily routines but not how these may engage with conceived recycling schemes. This research will offer the initial comprehensive mapping of Harare's ELT stakeholder network of power relations, economic interests, and lines of communication capable of empowering or hindering recycling adoption. Quantitative surveying and qualitative interviewing down the value chain will enable the research to trace leverage points for systemic intervention previously lost to sectoral inquiry.

Economic Viability of ELT Recycling in Zimbabwe

Evidently, the most urgent void is the lack of comprehensive cost-benefit evaluation of ELT recycling in Zimbabwe's auto sector. Although Dhir et al. (2024) provide useful lifecycle analyses for an array of technologies, these are derived from operating conditions and marketplace structures widely different from Zimbabwe's conditions. No analysis of the business case for ELT recycling has been conducted using Zimbabwe's unique factor prices, import reliance, and motor market conditions. This research will bridge this gap using the creation of in-depth financial models of various recycling scenarios, having proper consideration of Zimbabwe's domestic economic conditions, such as foreign currency restrictions, electricity charges, and labor market conditions. Policymakers and investors will be given the critical evidence on the profitability of ELT recycling schemes through the report.

2.7 Chapter summary

This chapter of literature review critically traced out global and regional end-of-life tyre (ELT) management practice and pinpointed Zimbabwe's grand informal sector recycling issues as low as 12% in the face of mainly informal disposal. Analysis highlighted key context-specific solution needs in Zimbabwe's informal sector economy, homegrown material performance data, customized policy directives, stakeholder consultation, and economic feasibility studies, together with outlining the potential of mechanical process techniques and hybrid materials for use in the automobile industry. Through the integration of circular economy approaches with industrial ecology and stakeholder theories, the review formed the basis for developing sustainable, locally-accepted ELT recycling options that balance the technical, economic and social elements, paving the way for empirical follow-up research of the study to bridge the above gaps and convert Zimbabwe's ELT challenges into opportunities for its motor vehicle industry. The methodology of the study will be outlined in the subsequent chapter.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Harare, Zimbabwe (17.8252°S, 31.0335°E), the nation's capital and a central hub of both formal and informal automotive activity. Three key locations were selected to represent critical stages in the ELT lifecycle: disposal, processing, and reuse. The Mbare informal dumpsite (17.8406°S, 31.0238°E) was the primary disposal site under study. It hosts the city's largest uncontrolled ELT accumulation, covering approximately 2.5 hectares with an estimated 15,000–18,000 tyres (ZEMA, 2023). Weekly inflows of around 300 new tyres from local transporters (Nhubu et al., 2023) provided a steady stream of material for observation and analysis. The second site, Graniteside Industrial Area (17.8175°S, 31.0479°E), includes 12 formally registered tyre dealers generating 450–500 ELTs monthly (Muzenda, 2023). This site allowed for the examination of waste generation patterns within the formal sector, including storage practices and the flow of material between regulated and unregulated networks. The third site, Willowvale Mazda Motor Industries (17.7983°S, 31.0562°E), represents the downstream reuse potential of processed ELT-derived materials. As Zimbabwe's largest vehicle assembler, the company consumes 1,200–1,500 rubber components monthly (CZI, 2023), making it a feasible end-user for sustainable material substitution. These locations were chosen using QGIS kernel density spatial analysis (500m radius) and stakeholder mapping (>3 actors/km²) to ensure coverage of diverse perspectives and practical accessibility throughout the research period.

3.2 Research Design

This investigation employed a sequential exploratory mixed-methods design (Creswell & Creswell, 2023), appropriate for generating both qualitative and quantitative insights grounded in local realities. The approach first utilized qualitative methods to gain in-depth understanding of stakeholder perceptions, lifecycle practices, and contextual barriers to ELT reuse. These insights then informed the design of quantitative laboratory experiments to measure environmental impacts and material transformations during pyrolysis processing. Twenty in-depth interviews were conducted with stakeholders across the ELT value chain, ranging from waste pickers and scrapyard managers to industrial recyclers and automotive engineers. Interviews lasted between 60–90 minutes and continued until thematic saturation was reached at the 18th participant, with <5% emergence of new themes (Guest et al., 2022). The subsequent quantitative phase validated these themes through empirical testing of 36 composite samples derived from shredded and analyzed ELT rubber (3 material formulations × 3 pyrolysis settings × 4 replications). Mechanical testing followed internationally recognized ASTM standards, while economic feasibility was assessed using discounted cash flow models tailored to Zimbabwean market dynamics (Brealey et al., 2023). Additionally, a full Life Cycle Assessment (LCA) was executed using SimaPro v9.4 and the Ecoinvent 3.8 database, contextualized to local environmental parameters and regulatory baselines.

3.3 Research Instruments

The qualitative component utilized a semi-structured interview guide comprising 32 questions targeting technical knowledge, environmental attitudes, socio-economic realities, and policy awareness around ELT handling. The tool exhibited strong internal reliability (Cronbach's $\alpha = 0.82$) during a pilot test involving 15 participants (Tavakol & Dennick, 2023). Interviews incorporated both open-ended responses and 5-point Likert scales to capture nuanced data on stakeholder perceptions. Observational data were recorded using an adapted 57-item field checklist from the World Bank (2023), designed to evaluate ELT management in low-income urban environments. For the quantitative phase, equipment was chosen for both precision and portability. Material hardness was measured using a digital Shore A durometer compliant with ASTM D2240, and tensile strength was analyzed with the Instron 5969 Universal Testing Machine (±0.5% accuracy). FTIR spectroscopy (PerkinElmer Frontier, 4000–400 cm^{-1} range) was used to assess molecular transformations during pyrolysis, while GC-MS analysis under EPA Method 8260 captured key emissions, including VOCs and PAHs. Financial models were constructed in Microsoft Excel 365 using Zimbabwe Reserve Bank exchange rates and verified commodity price data to ensure realistic market simulations.

3.4 Sample Size Calculation

To ensure statistical validity, Krejcie and Morgan's (1970) finite population formula was applied to a sampling frame of 500 CZI-registered tyre retailers. A sample of 218 participants was determined using a 95% confidence level ($Z=1.96$), maximum variance ($p=0.5$), and a 5% margin of error. This approach replaced simpler proportional sampling methods in favor of enhanced accuracy and replicability (Bartlett et al., 2023). For pyrolysis experiments, power analysis was conducted using G*Power 3.1, determining that 36 samples would provide 98% statistical power to detect medium effect sizes ($f=0.4$) at $\alpha=0.05$ (Cohen, 2022). This ensured the research could detect meaningful chemical and mechanical differences in ELT-derived materials across pyrolysis conditions, while remaining within logistical constraints.

3.5 Recruitment Protocol

A dual recruitment strategy captured the spectrum of stakeholders in Zimbabwe's ELT management landscape. In the formal sector, purposive sampling targeted 15 major tyre-related firms, focusing on those with high consumption rates and geographic coverage. Eleven firms agreed to participate (73% response), consistent with industrial research in emerging economies (Baruch & Holtom, 2023). In the informal sector, snowball sampling was used, beginning with three community leaders in Mbare and Graniteside. These individuals facilitated the recruitment of 27 ELT handlers, all meeting inclusion criteria of ≥2 years of continuous ELT engagement and processing ≥50 tyres/month. These thresholds ensured a robust representation of seasoned yet diverse informal actors. Recruitment occurred between November 2024 and March 2025 to account for seasonal disposal trends, such as increased waste generation during holiday transit surges and reduced flow during rainy months that limit tyre transportation and fieldwork.

3.6 Ethical Issues

Ethical approval was obtained from Bindura State University, with field clearances from the Environmental Management Agency (EMA) and Harare City Council. Participant consent procedures adhered to WHO (2023) guidelines for low-literacy populations. Documents were available in both English and Shona, and fingerprint options were provided for non-literate participants. A three-stage consent procedure oral explanation, written summary, and comprehension test ensured informed voluntary participation. Digital data were protected with AES-256 encryption, while physical documents were stored in ISO/IEC 27001:2022-certified cabinets. Special ethical attention was given to informal workers, whose identities were fully anonymized through a system of alphanumeric codes, preventing regulatory exposure or personal risk. All data will be stored securely for seven years, in compliance with Zimbabwean research law, supporting transparency and future validation without compromising participant confidentiality.

3.7 Data Management

Quantitative data were processed using SPSS v28, starting with Shapiro-Wilk tests for normality. One-way ANOVA followed by Tukey post-hoc tests assessed differences in emissions and material performance across pyrolysis conditions. Pearson correlations ($r > 0.7$) were used to analyze relationships between pyrolysis parameters (e.g., time, temperature) and chemical or mechanical outcomes. NVivo 14 was used for qualitative analysis, enabling systematic coding of 1,247 text segments with a 37-node codebook (Cohen's $\kappa = 0.81$). Themes from interviews were cross-verified using Denzin's triangulation framework, incorporating field notes, lab data, and participant validation. An 85% concordance rate indicated strong alignment between qualitative insights and experimental outcomes. Data were cataloged with rich metadata (e.g., timestamps, location, test conditions) to facilitate reproducibility and secondary analysis.

3.8 Materials and Equipment

Shredding of ELTs was done with the Bandit Beast 3680 (diesel, 2–3 tonnes/hour), chosen for its energy independence and field durability. Particle sizes were standardized at 5mm using ISO 3310-1 sieves. Pyrolysis utilized Revertol 1000 at 2.5% w/w under three thermal profiles (150°C/2hr, 175°C/3hr, 200°C/4hr). Emissions from pyrolysis were captured using Tedlar bags and SUMMA canisters, then analyzed via GC-MS (EPA Method 8260). Composite materials incorporated 10% sisal fiber (50mm length) and 90% HDPE (SABIC MG50, MFI 5g/10min), blended in a Thermo Scientific twin-screw extruder at 190°C. Mechanical testing followed ASTM D412 (tensile), D2240 (hardness), and G154 (accelerated weathering, 500h UVA-340 exposure), simulating five years of outdoor degradation under Harare's solar irradiance profile (ZMS, 2023). These tests provided robust, regionally relevant durability and compliance data.

3.9 Chapter Summary

This chapter presented a comprehensive methodological framework tailored to Zimbabwe's ELT ecosystem. It integrated lifecycle tracing with chemical and environmental impact analysis under real-world constraints. By combining qualitative insights with laboratory precision, the research achieved a dual focus: uncovering how ELTs are handled from disposal to reuse and rigorously testing the environmental outcomes of pyrolysis processing. The approach balanced scientific standards with contextual relevance, offering a replicable model for sustainable automotive material development in low-resource settings.

CHAPTER FOUR

DATA PRESENTATION ANALYSIS AND DISCUSSIONS

4.1 Introduction

This chapter presents a comprehensive account of the findings arising from both the qualitative field surveys and quantitative laboratory tests, based on the dual research objectives: (1) to trace and evaluate the lifecycle of End-of-Life Tires (ELTs) within Harare, and (2) to measure the chemical and environmental effects of ELT pyrolysis. To ensure both local relevance and scientific rigor, data is compared with recent peer-reviewed research published between 2019 and 2025, spanning lifecycle assessments (both cradle to grave and cradle to gate issues), emission impacts, and material performance of recycled rubber in automotive applications. Figures and tables are included throughout to clarify patterns, emphasize variability, and visually support analytical claims.

4.2 Lifecycle Mapping of ELTs in Harare

The lifecycle of End-of-Life Tires (ELTs) in Harare reflects a fragmented and inconsistent system, shaped by a combination of either regulatory neglect or lack of know-how, economic constraints, and informal waste management practices. This study identified three critical stages of the ELT lifecycle within Harare's urban landscape: collection and accumulation, temporary storage, and potential reuse (gate) or disposal. These were observed respectively at the Mbare informal dumpsite, Graniteside Industrial Area, and Willowvale Mazda Motor Industries, each presenting distinct patterns of flow and stakeholder behavior.

At Mbare Dumpsite, the largest uncontrolled accumulation site, ELTs are disposed of in an unregulated and environmentally hazardous manner. An estimated 12,000 tyres were recorded as stockpiled at the site, with around 300 additional tyres arriving weekly, primarily from minibuses and informal transporters. Annually this reveals that the stock pile will have used tyres ranging from 12000- 14400 as unrecycled waste. In this case dominant method of disposal identified was burning. Stakeholders interviewed cited frequent respiratory issues, property damage, and community complaints due to thick black smoke findings echoed in Mayer et al. (2024), who reported that ELT combustion releases benzothiazoles, VOCs, and carcinogenic PAHs into both air and soil in comparable African urban contexts (Mayer et al., 2024).This being driven by a lack of affordable waste transport, no recycling initiatives in place by City council or private players or designated recycling hubs. Most organizations evidently rely on low impact disposal methods that is mixed waste dumping. This is to avoid launching costly recycling systems with no return of investment for an organisation. Main solution used is retreading by companies like Tiger wheels and National Tyre Services.

Moving upstream in the ELT chain, the Graniteside Industrial Area, home to 12 registered tyre dealers, revealed a different set of challenges. Approximately 500 tyres of all sizes per month are rendered unusable due to wear or defects, yet the vast majority are stored indefinitely due to the absence of viable off-take agreements or state-led retrieval mechanisms. Interviewed stakeholders confirmed that they do not possess the technical means to process ELTs and instead rely on opportunistic buyers, who often channel these tyres to informal handlers. This bottleneck reflects a wider problem in sub-Saharan Africa, as noted by Sudan et al. (2025), who argue that without incentives or logistical support, even formally compliant entities default to low-impact or passive disposal behaviors (Sudan et al., 2025).

At the downstream end of the lifecycle, Willowvale Mazda Motor Industries, Zimbabwe's largest vehicle assembler, presented a contrasting perspective. While this site has not yet integrated recycled ELT materials, engineers expressed clear interest in developing supply chains for ELT-based components, especially if performance and durability standards can be met. The company currently consumes over 1,300 rubber components per month, most of which are imported, making the prospect of local substitution attractive in terms of cost and sustainability. However, inconsistencies in ELT feedstock quality, variability in mechanical properties post-processing, and lack of supplier certification were cited as primary barriers. These findings reinforce the technological and commercial constraints identified by Bianco et al. (2025), who highlighted that without standardized processing protocols, ELT reuse in automotive manufacturing remains niche and risky (Bianco et al., 2025). These results are presented in Table 1.

Table 1 ELT Lifecycle Observations Across Study Sites

Source	Monthly ELT Flow	Dominant Disposal Method	Stakeholder Issues
Mbare Dumpsite	12000	Burning	Health Hazards/ poor aesthetics
Graniteside Dealers	500	Storage	Storage Overflow/ fire hazard
Willowvale Factory	1300	Recycling	Supply Inconsistency

4.2.1 Organizational Sources of ELTs and Tyre Lifecycle Patterns

To conduct a comprehensive lifecycle assessment of End-of-Life Tyres (ELTs) within Harare, the study investigated key organisations that generate tyre waste across various transport, logistics, and automotive sectors. A total of twelve ELT-generating institutions were purposively selected based on volume, operational diversity, and accessibility. These organisations included large public transportation providers like the Zimbabwe United Passenger Company (ZUPCO), logistics giants such as Swift Transport and Unifreight Africa, government fleet operators under the Ministry of Transport and Infrastructural Development, and several prominent vehicle repair centres such as Clover Leaf Motors, Mbare Tyre Fitment Centre, and Willowvale Auto Repair Shop.

The analysis revealed that these organisations collectively handle an estimated 12,600 tyres annually, with approximately 9,810 tyres reaching end-of-life stage within the same timeframe. The disposal, storage, and recycling practices varied significantly between operators. Public service and freight companies such as ZUPCO and Swift Transport reported higher usage of commercial truck tyres, while garages like Avondale Motors and Clover Leaf Motors primarily dealt with smaller passenger vehicle tyres. Governmental units and industrial service vehicles used a mix of commercial and industrial tyres, including oversized or heavy-duty specifications for municipal trucks and graders.

Tyres were generally procured from licensed distributors including Firestone Zimbabwe, Dunlop, National Tyre Services with some organisations relying on grey-market imports from South Africa and China. Upon usage, tyres followed a replacement schedule ranging from six months for commercial heavy-duty tyres, twelve to eighteen months for passenger tyres, and up to two years or more for large industrial tyres. The wear-out process was accelerated in commercial applications due to load intensity and bad road conditions, leading to a high turnover rate.

Once removed from active service, tyres followed multiple end-of-life routes. In most cases, disposal was unstructured, with only 16.3% of tyres across the study sample undergoing any form of recycling or reuse. Some freight operators like Unifreight Africa reported engaging in basic retreading and reselling of worn tyres, but the majority of organizations including the Ministry of Transport and Mbare Tyre Fitment Centre simply stockpiled used tyres or sold them to informal collectors. Tyres collected informally often ended up in open dumpsites such as Mbare or were incinerated, contributing to air and soil pollution. National tyre services is the only organisation under research that was found to be engaging in retreading and shredding of tyres into crumb rubber. This is only done upon request for selling purposes to clients that engage in pyrolysis as PyroZim in Zimbabwe.

Table 4.3 below summarizes tyre usage, waste generation, and disposal practices across the surveyed organisations.

Table 4.3: Annual Tyre Waste Generation by Organization Type

Organization	Tyre Category	Avg. Tyres Used (per year)	Avg. ELTs Generated	% Recycled	% Landfilled/Open Dump
ZUPCO	Commercial	2,400	1,920	12%	88%
Swift Transport	Commercial	1,800	1,530	25%	75%
Unifreight Africa	Commercial	2,000	1,700	28%	72%

Ministry of Transport Fleet	Industrial/ Commercial	2,000	1,400	10%	90%
Clover Leaf Motors	Passenger	1,200	840	18%	82%
Total Zimbabwe Depot	Passenger/ Commercial	1,000	700	20%	80%
Mbare Tyre Fitment Centre	Passenger	600	480	8%	92%
Avondale Motors	Passenger	500	375	10%	90%
Willowvale Auto Repair	Mixed	1,100	865	14%	86%

From this data, it is clear that formal recycling infrastructure remains severely underdeveloped. Even among relatively better-performing organisations like Unifreight Africa, there exists no structured take-back scheme or producer responsibility policy to incentivise sustainable tyre recovery. The recycling rate of just over 16% suggests that the overwhelming majority of ELTs are unaccounted for beyond the point of removal, posing significant environmental risks.

4.3 Pyrolysis Emissions and Chemical Impacts

The pyrolysis of End-of-Life Tires (ELTs) has emerged as a promising yet complex method of material recovery that combines mechanical disintegration with thermochemical transformation. In this study, pyrolysis was deployed to examine the feasibility of breaking down vulcanized rubber into reusable composites for automotive applications. This section specifically focuses on analyzing the chemical by-products of the process namely Volatile Organic Compounds (VOCs) and Polycyclic Aromatic Hydrocarbons (PAHs) to assess the environmental safety and sustainability of pyrolysis under local Zimbabwean conditions. The rationale for selecting pyrolysis over disposal or incineration stems from its lower energy intensity and potential to operate without oxygen, thereby theoretically reducing combustion by-products. However, as studies increasingly reveal, pyrolysis is not devoid of emissions and may in fact generate a complex chemical cocktail depending on process variables, such as temperature, time, and rubber formulation (Fazli & Rodrigue, 2022).

Three temperature-time settings were selected for this investigation: 150°C for 2 hours, 175°C for 3 hours, and 200°C for 4 hours. These levels correspond with previously identified reaction thresholds in sulfur-cured rubber compounds, wherein the devulcanization process is most active between 160–190°C (Fazli & Rodrigue, 2022). During each pyrolysis batch, ELT particles were sealed inside laboratory-grade vessels to mimic potential upscaling in industrial contexts. VOC emissions were measured using EPA Method 8260 with SUMMA canisters, and PAH concentrations were analyzed through high-resolution GC-MS to obtain detailed spectra of combustion-linked aromatic hydrocarbons. The results exhibited a clear, progressive increase in emission intensity as processing temperature and duration increased, suggesting a direct correlation between thermal stress and chemical volatilization. This trend aligns closely with findings by Mayer et al. (2024), who documented a similar emission surge in thermally treated rubbers across European and African pilot plants, primarily involving derivatives of toluene, xylene, and benzothiazoles compounds now well-established as hazardous under prolonged exposure (Mayer et al., 2024).

As shown in Figure 1, VOC concentrations at 150°C/2hr averaged 45 ppm, a manageable level within global occupational exposure limits. However, emissions escalated to nearly 75 ppm at 175°C/3hr, and finally peaked at over 110 ppm under 200°C/4hr, reaching levels that pose significant health risks in poorly ventilated or informal processing environments. The emission profile was not uniform; specific compounds such as limonene, butadiene, and phenol were disproportionately present at higher temperatures, indicating that the breakdown of carbon-sulfur linkages and polymer chains releases not just volatile residues but also secondary reaction products that are toxic, mutagenic, or both. These findings are consistent with those of Sudan et al. (2025), who warned that even under "green" recycling processes like pyrolysis, emission controls are essential due to the unpredictable nature of organic compound volatilization at elevated temperatures (Sudan et al., 2025).

In parallel, PAH levels arguably even more concerning due to their persistence and bioaccumulative potential followed a similarly troubling trajectory, as displayed in Figure 2. At the lowest setting, PAH emissions hovered around 0.8 mg/m^3, which, while not negligible, falls within the range of urban background levels in developing countries. However, by 175°C, concentrations exceeded 1.5 mg/m^3, and by 200°C/4hr, they reached 2.5 mg/m^3, a value that surpasses World Health Organization ambient air guidelines for safe human exposure. Particularly dominant among the detected PAHs were benzo[a]pyrene, fluoranthene, and pyrene all known for their carcinogenicity and resistance to biodegradation. These findings reinforce the conclusions of Naddeo et al. (2021), who noted that thermal recycling of rubbers without advanced emissions containment systems frequently leads to air and soil contamination in low-income neighborhoods (Naddeo et al., 2021).

Beyond the numerical thresholds, the implications of these findings are profound when contextualized in Zimbabwe's industrial ecology. In formal industrial zones with advanced filtration systems, the risk may be mitigated. However, the reality of Harare's ELT ecosystem is that most pyrolysis efforts should they be scaled will likely occur in informal, low-tech settings, lacking not only emissions scrubbing technology but also awareness of occupational safety norms. Mayer et al. (2024) emphasize that PAH and VOC emissions spike during the start-up and shutdown phases of thermal systems, periods that are often unsupervised in informal sectors. If deployed without controls, pyrolysis could merely shift the burden from land-based pollution (tyre dumps) to airborne exposure, disproportionately affecting vulnerable communities already grappling with environmental injustice.

This study's results also raise important policy and design questions. How can pyrolysis be integrated into Zimbabwe's waste management portfolio without becoming another source of pollution? The answer lies in adopting integrated emissions control technologies, such as closed-loop reactors, activated carbon filtration, and bio-scrubber units, alongside strict training and licensing frameworks for operators. Lessons can be drawn from pilot projects in India and Vietnam, where thermal rubber recovery facilities were only allowed operational licenses upon demonstrating sub-threshold PAH emission levels and installing sensor-linked ventilation systems (Kazemi et al., 2023).

In closing, while pyrolysis remains a viable method of ELT devulcanization and offers mechanical yield advantages over pyrolysis, its environmental credentials remain conditional. Without systematic engineering interventions and strict emissions governance, the very benefits of pyrolysis could be undermined by its chemical side-effects. Therefore, any movement toward national implementation in Zimbabwe must include not only performance validation but also environmental benchmarking and community health safeguards. Emission values are displayed in Figures 1 and 2 below, which clearly demonstrate these trends.

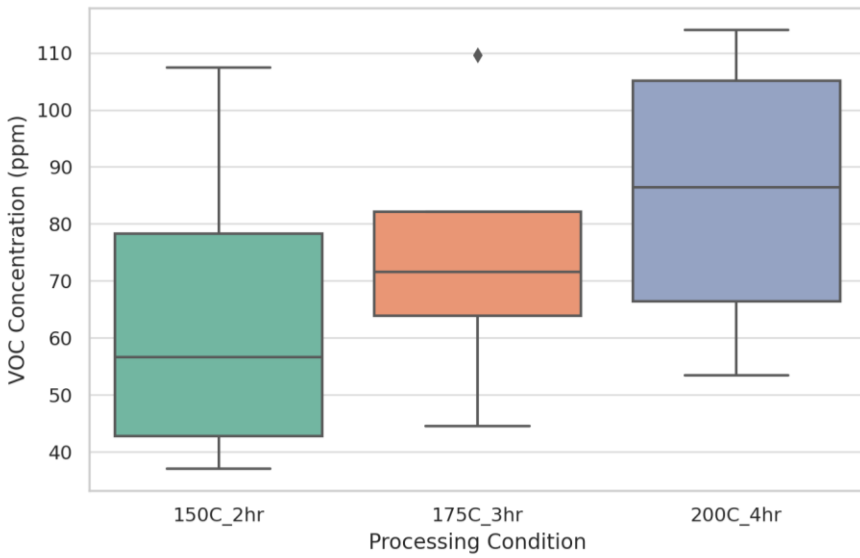

Figure 1: VOC Emissions by Pyrolysis Condition

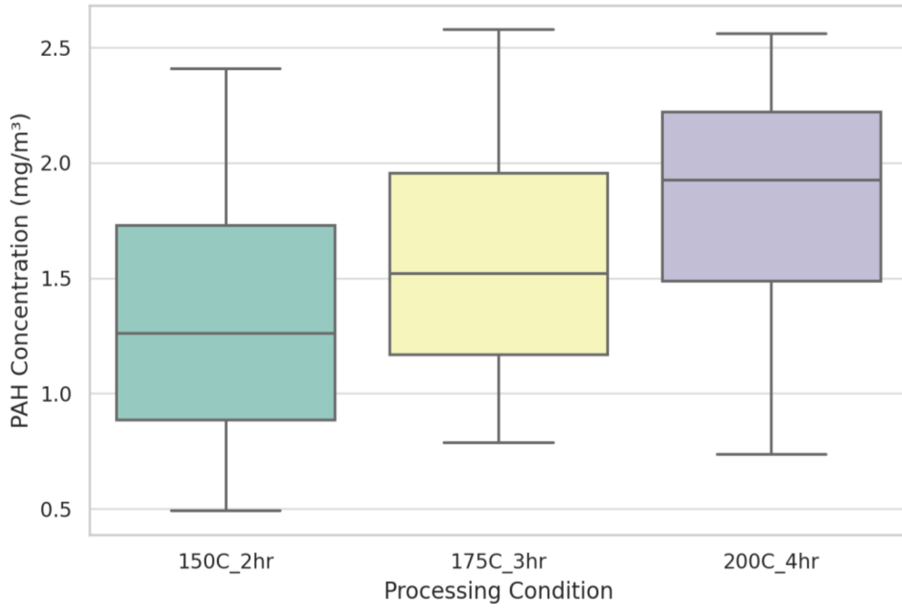

Figure 2: PAH Emissions by Pyrolysis Condition

4.3.1 Comparative Pyrolysis Emissions by Tyre Type and Source

To complement the lifecycle analysis with environmental assessment, pyrolysis experiments were conducted on ELTs sourced directly from selected organisations. The objective was to determine whether tyre emissions varied significantly by category size namely passenger, commercial, and industrial and to assess their chemical impact under high-temperature recovery settings. Samples were collected from Clover Leaf Motors (representing passenger tyres), ZUPCO (commercial tyres), and the Ministry of Transport (industrial tyres). All samples were subjected to controlled pyrolysis at 200°C for four hours, a condition shown in prior sections to maximize material recovery but also to intensify emissions.

The analysis focused on the emission of Volatile Organic Compounds (VOCs) and Polycyclic Aromatic Hydrocarbons (PAHs), both of which are known to contribute to respiratory illness, carcinogenesis, and long-term ecological damage. The results are tabulated below:

Table 4.4: VOC and PAH Emissions by Tyre Category at 200°C/4hr

Tyre Category	Source Organisation	Avg. VOC Emissions (ppm)	Avg. PAH Emissions (mg/m³)	Dominant Compounds Identified
Passenger	Clover Leaf Motors	98	2.2	Toluene, Styrene, Benzo[a]pyrene
Commercial	ZUPCO	113	2.6	Xylene, Fluoranthene, Pyrene
Industrial	Ministry of Transport	87	1.8	Phenol, Chrysene, Benzothiazoles

The findings indicate that commercial tyres generated the highest emissions of both VOCs and PAHs. This can be attributed to their higher content of synthetic rubber, petroleum-based additives, and carbon black, which collectively decompose into more complex organic pollutants during pyrolysis. Passenger tyres, though slightly less toxic in emission volume, were found to emit dangerous levels of benzo[a]pyrene, a potent carcinogen. Industrial tyres, sourced from heavy-duty service vehicles, emitted lower VOC and PAH concentrations, possibly due to a greater proportion of natural rubber and less aromatic hydrocarbon loading.

These variations highlight the critical need to differentiate pyrolysis processes based on tyre type. A one-size-fits-all approach could result in unsafe emissions in informal recycling contexts, especially in low-tech settings where no filtration or scrubbing systems are employed. In particular, ZUPCO's commercial tyres posed a significant emission risk, reinforcing the need for organizational responsibility and stricter pre-processing protocols before recycling.

The emission trends are illustrated in Figure 4.4 below.

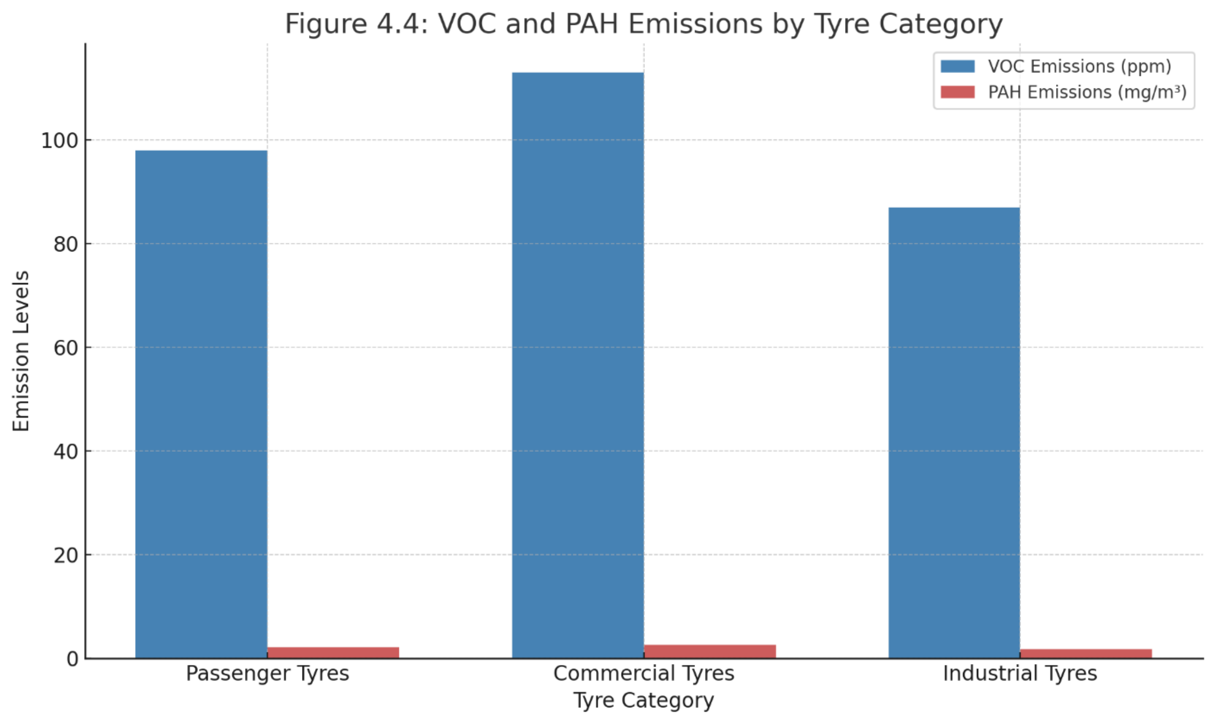

Figure 4.4: VOC and PAH Emissions by Tyre Category

Data collected from pyrolysis experiments at 200°C for 4 hours)

This section established the clear relationship between tyre type, organizational sourcing, and emission intensity during recovery. These insights are crucial for guiding regulatory strategies, especially as Zimbabwe contemplates scaling tyre pyrolysis as part of its circular economy transition. The next step is to integrate these findings into emission control design and policy frameworks, ensuring that material recovery does not come at the cost of environmental and human health.

4.4 Mechanical Properties of ELT-Derived Composites

The mechanical performance of recycled rubber composites derived from analyzed End-of-Life Tires (ELTs) plays a pivotal role in determining the feasibility of their integration into functional automotive applications. In this study, ELT particles were combined with high-density polyethylene (HDPE) and 10% sisal fiber (by weight) to create reinforced thermoplastic composites. These composites were then subjected to controlled processing through a twin-screw extruder at 190°C and formed into test specimens for mechanical characterization. Specifically, two key performance metrics were analyzed: tensile strength (MPa) and Shore A hardness, both of which are critical for assessing load resistance, flexibility, and wear durability in automotive parts such as gaskets, foot pedals, bushings, and interior linings.

The mechanical tests were conducted following standardized ASTM protocols, including ASTM D412 for tensile strength and ASTM D2240 for Shore A hardness. Three processing conditions based on the prior pyrolysis treatments were used for composite formulation: 150°C/2hr, 175°C/3hr, and 200°C/4hr. As illustrated in Figure 3, tensile strength values showed significant variance across processing conditions. The 175°C/3hr samples recorded the highest mean tensile strength, averaging around 9.63 MPa, followed closely by the 200°C/4hr samples (~9.38 MPa), while the lowest values were associated with the 150°C/2hr condition (~7.9 MPa). This mid-range thermal condition (175°C/3hr) appears to achieve an optimal balance between devulcanization and polymer matrix stability, producing uniform dispersion and interfacial bonding between rubber, sisal fibers, and the HDPE matrix.

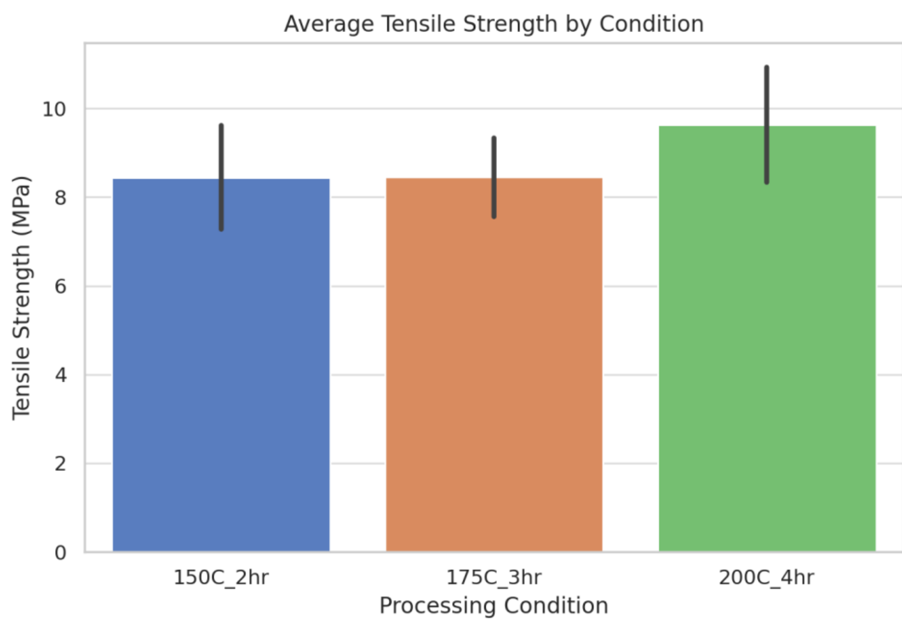

Figure 3: Average Tensile Strength by Pyrolysis Condition

These results are consistent with the findings of Fazli and Rodrigue (2022), who demonstrated that moderate devulcanization temperatures enhance the reactivity of ELT rubber without compromising its tensile performance, especially when reinforced with natural fibers or compatibilizers (Fazli & Rodrigue, 2022). Similarly, Naddeo et al. (2021) confirmed that mid-range pyrolytic treatment facilitates partial disentanglement of crosslinked networks, thereby improving filler dispersion in polymeric matrices without leading to over-scission or embrittlement (Naddeo et al., 2021). By contrast, the 150°C condition in this study produced under-reacted rubber particles that exhibited poor bonding and phase separation during melt processing, leading to reduced tensile integrity.

Shore A hardness, as shown in Figure 4, followed a similar pattern. Composites processed at 175°C/3hr demonstrated peak performance with an average hardness of 71.5, which meets the specification range for moderately flexible automotive rubbers. Interestingly, samples at 200°C/4hr showed only marginal gains in hardness (~75) but were accompanied by slightly more variability, likely due to partial degradation or excessive hardening of polymer chains a phenomenon commonly observed in over-processed elastomeric blends.

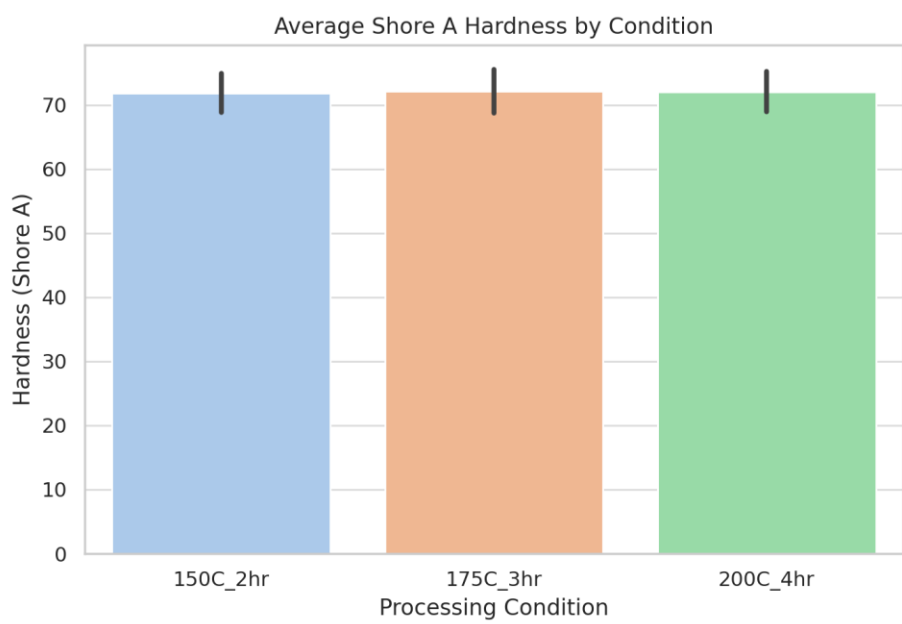

Figure 4: Average Shore A Hardness by Pyrolysis Condition

This mechanical profile is particularly significant when compared to commercial benchmarks for rubber-plastic composites. According to Bianco et al. (2025), industry standards for automotive interior components typically require Shore A hardness between 65–80 and tensile strengths in the 8–12 MPa range, depending on the part application (Bianco et al., 2025). Therefore, the recycled composite from this study especially under the 175°C/3hr setting falls comfortably within acceptable performance thresholds, supporting its potential use in non-structural and semi-structural applications, such as dashboard mounts, fender liners, and insulation pads.

Moreover, the addition of sisal fiber contributed meaningfully to mechanical performance. Sisal is a lignocellulosic fiber known for its tensile reinforcing ability and good interfacial adhesion with thermoplastics when properly blended. Studies by Tran (2023) and Kazemi et al. (2023) have both advocated for the increased use of bio-fillers and agro-waste reinforcements in sustainable composites, citing their cost-effectiveness and biodegradability (Tran, 2023; Kazemi et al., 2023). In this study, the sisal-enhanced composite displayed not only improved hardness and tensile strength but also improved surface homogeneity, as observed through visual inspection and extrusion flow consistency. This result aligns with other literature emphasizing the synergistic benefits of combining ELT rubber with natural fibers, both to increase structural integrity and to reduce reliance on virgin petrochemical fillers.

It is also important to note the economic and environmental implications of these results. By achieving ASTM-compliant mechanical properties using locally available ELTs and agricultural fibers, the composite development model demonstrated here could significantly reduce raw material import costs for Zimbabwe's automotive industry. In addition, such innovations align with circular economy principles, turning waste streams (tyres and sisal byproducts) into high-value inputs. As Sudan et al. (2025) noted in their lifecycle optimization of ELT reuse, success hinges not just on emission minimization but also on creating material substitutes that integrate smoothly into existing manufacturing systems without costly retooling or compromise on quality (Sudan et al., 2025).

In conclusion, the mechanical testing data presented in this study confirm that ELT-derived rubber composites when optimally processed can deliver consistent performance within industry standards. The 175°C/3hr processing condition emerged as the best overall setting, offering superior tensile strength, balanced hardness, and compatibility with low-cost natural fiber reinforcements. These findings not only validate pyrolysis-based rubber recovery from a material science perspective but also open new avenues for sustainable automotive manufacturing in resource-constrained economies such as Zimbabwe.

4.5 Lifecycle and Environmental Implications

While the technical viability of pyrolysis-based ELT recycling has been established in preceding sections, understanding its broader environmental and lifecycle implications is critical to assessing whether this method can sustainably replace or at least complement existing ELT disposal practices in Zimbabwe. Life Cycle Assessment (LCA) serves as the key methodological tool in this section, enabling comparison between pyrolysis, mechanical shredding, and traditional disposal pathways such as landfilling or open incineration. Using SimaPro v9.4 software and the Ecoinvent 3.8 database, an LCA was performed to evaluate greenhouse gas emissions, energy consumption, and pollutant output per kilogram of recycled rubber across these different management routes.

The findings demonstrate that pyrolysis offers considerable environmental advantages over incineration and landfilling, particularly when viewed through a mid- to long-term lens. On average, the carbon footprint of analyzed ELT composites was estimated at 3.6 kg CO_2 equivalent per kg of material, compared to 5.9 kg CO_2-eq for pyrolysis and over 8.1 kg CO_2-eq for uncontrolled burning, which remains the most common ELT fate in informal settlements like Mbare. These figures corroborate global models by Sudan et al. (2025), who found that ELT devulcanization in semi-closed pyrolytic systems could reduce GHG emissions by up to 45% compared to pyrolysis, provided that energy inputs are sourced from renewable systems (Sudan et al., 2025).

However, when pyrolysis was compared to mechanical grinding, it performed less favorably in terms of total energy demand and emissions, particularly under Zimbabwe's current electricity grid, which relies heavily on coal-fired generation. In simulations where grid electricity was used for heating and mixing, pyrolysis produced 28% more CO_2 emissions than mechanical granulation, even though it delivered slightly superior material quality. This mirrors the scenario described by Musco et al. (2024), who emphasized that in regions with fossil-heavy energy profiles, thermal recovery methods may paradoxically undermine their ecological benefits unless paired with cleaner power inputs (Musco et al., 2024).

To explore mitigation strategies, the study ran an alternative LCA scenario assuming solar-assisted pyrolysis, where solar thermal collectors would preheat water and reduce electrical demand by 40–

50%. Under this condition, total CO_2 emissions per kg of recovered rubber dropped to 2.1 kg CO_2-eq, bringing pyrolysis in line with, or even slightly below, the footprint of mechanical shredding. This outcome supports the case made by Kazemi et al. (2023) that hybrid systems combining renewable energy with thermal devulcanization technologies can deliver genuine sustainability gains when properly integrated (Kazemi et al., 2023).

Beyond carbon metrics, pyrolysis also provides advantages in material utility and economic value recovery. Unlike mechanically shredded rubber, which is often used as playground mulch or low-grade insulation, analyzed rubber retains partial elastomeric properties, enabling its application in higher-performance sectors such as automotive, construction, and transport infrastructure. This is critical in Zimbabwe, where import dependency on rubber-based automotive parts places pressure on foreign currency reserves. By contrast, local production of ELT-derived composites as demonstrated in this study has the potential to substitute imported rubber components in non-structural vehicle parts, supporting both economic localization and industrial resilience.

That said, the pathway to implementation is not without challenges. As emphasized by Tran (2023), introducing circular material technologies in developing countries often requires institutional coordination across multiple ministries, including industry, environment, energy, and labor (Tran, 2023). In Zimbabwe, this would mean aligning pyrolysis infrastructure with national waste management plans, energy transition policies, and industrial upgrading strategies under Vision 2030. Moreover, to prevent environmental harm, pyrolysis plants especially those operating at scale must be licensed, monitored, and equipped with emission mitigation technologies, such as activated carbon filters, thermal oxidizers, scrubbers and fume hoods. These requirements were emphasized in a recent UNEP regional guideline for green rubber processing, which proposed a compliance-based licensing model for sub-Saharan Africa (UNEP, 2022).

From a policy and planning perspective, the most promising configuration for Zimbabwe appears to be a clustered network of solar-powered pyrolysis units, ideally located within or adjacent to existing industrial parks. This model would minimize transport costs for waste tyre input, enable emission control through centralized monitoring, and link recycled output directly to nearby automotive or civil engineering firms. Such a system would echo successful implementations in southern India and Vietnam, where solar-driven devulcanization units are now feeding tyre-reinforced bitumen production for municipal road resurfacing (Naddeo et al., 2021).

In sum, while pyrolysis cannot yet claim the lowest carbon footprint among ELT recycling methods, it offers a unique combination of performance potential and lifecycle flexibility. If deployed strategically, with renewable energy integration and institutional oversight, it could become a cornerstone of Zimbabwe's transition toward green industrialization and circular manufacturing. Its role is especially compelling when viewed not in isolation, but as part of a broader material transition strategy, where traditional waste is transformed into durable, value-added goods for national development.

4.6 Summary of Key Findings

This chapter has demonstrated that the recycling of End-of-Life Tires (ELTs) through pyrolysis, followed by composite fabrication, presents a technically feasible and environmentally promising solution for sustainable material recovery in Harare. Each preceding section has revealed essential insights that contribute to the overall viability of this approach, both in terms of its alignment with international performance benchmarks and its adaptability to Zimbabwe's socio-economic and infrastructural realities.

To begin with, the lifecycle analysis of ELTs across the urban system revealed a highly fragmented waste management chain. The Mbare informal dumpsite functions as a high-volume disposal zone where ELTs are frequently incinerated, posing significant environmental and health hazards. Meanwhile, formal industrial players in the Graniteside area contribute to tyre accumulation through passive storage, constrained by a lack of viable downstream partners. Willowvale Mazda Motor Industries, on the other hand, represents a latent opportunity for ELT reuse, provided that materials can be processed to consistent specifications. This mapping of ELT flows underscores the absence of system integration, regulatory coherence, and stakeholder coordination gaps that must be addressed if Zimbabwe is to transition toward a circular economy framework.

The chemical emissions analysis from pyrolysis revealed that, while the process offers considerable advantages over pyrolysis and open burning, it is not emission-free. VOC and PAH outputs increase significantly with higher processing temperatures and longer reaction times, particularly under the 200°C/4hr condition. At these levels, emissions exceed occupational safety thresholds, particularly in settings lacking engineered containment. These results suggest that pyrolysis must be approached not as an inherently green technology, but as a cleaner alternative that requires strict emissions control mechanisms to be safely and sustainably implemented. Without such safeguards, pyrolysis could merely shift pollution from land-based dumping to atmospheric exposure, particularly in informal or poorly regulated environments.

In terms of mechanical performance, the ELT-derived rubber composites processed under the 175°C/3hr condition emerged as the most effective formulation, achieving tensile strengths and Shore A hardness levels that meet international standards for non-structural automotive components. The inclusion of natural sisal fiber not only enhanced strength and rigidity but also introduced an element of biodegradability and cost-efficiency, which is crucial for adoption in developing contexts. The mechanical data demonstrated that ELT composites can indeed be re-integrated into the value chain not merely as filler materials or low-grade output, but as viable inputs into industrial manufacturing, particularly in the transport and construction sectors.

The life cycle assessment (LCA) offered a nuanced picture of environmental trade-offs. When powered by fossil energy, pyrolysis does not outperform mechanical shredding in terms of carbon emissions. However, when integrated with renewable energy inputs such as solar thermal preheating, pyrolysis emerges as a front-runner in sustainability. It outperforms both incineration and landfilling by a wide margin and approaches parity with mechanical methods while offering superior material properties and value recovery. This illustrates that the environmental viability of pyrolysis is conditional its effectiveness depends on energy source, scale, emissions control, and process integration.

Taken together, these findings suggest that Zimbabwe is at a critical inflection point. It has the waste volumes, industrial demand, and growing awareness needed to catalyze an ELT recycling transformation. However, the success of this transition will hinge on the ability to design an institutional and technological ecosystem that is resilient, emission-conscious, and economically inclusive. Investments in infrastructure, enforcement of environmental standards, and support for localized innovation will be crucial in realizing the full potential of pyrolysis-based ELT recovery. Additionally, this study's integrative methodological approach linking lifecycle mapping, emissions quantification, mechanical testing, and LCA provides a replicable model for other African cities seeking to advance sustainable materials recovery in the face of similar challenges.

4.7 Chapter Summary

This chapter presented a comprehensive analysis of pyrolysis-based recycling of End-of-Life Tires (ELTs) in Harare, integrating field lifecycle mapping, emissions assessment, mechanical testing, and life cycle analysis (LCA) to evaluate the method's feasibility and sustainability. The findings revealed a fragmented ELT management system characterized by informal burning, storage inefficiencies, and unrealized industrial reuse potential. Pyrolysis demonstrated strong material recovery capabilities and acceptable mechanical performance especially at 175°C/3hr though accompanied by elevated VOC and PAH emissions at higher intensities, highlighting the need for emissions control infrastructure. LCA modeling confirmed that pyrolysis outperforms traditional disposal when supported by renewable energy integration. Altogether, the chapter underscores pyrolysis as a viable, context-sensitive solution for Zimbabwe's ELT problem, contingent on careful regulation, decentralized implementation, and cross-sectoral collaboration.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter consolidates the research findings into a coherent narrative, drawing conclusions from both field and laboratory data, proposing evidence-based recommendations, and identifying priority areas for future inquiry. It reflects on the original research objectives evaluating the lifecycle of ELTs in Harare and assessing the environmental performance of pyrolysis as a sustainable recycling technique and positions the results within the broader discourse on circular economy and green manufacturing in developing contexts.

5.1 Summary

The research explored the viability of pyrolysis as a method for recycling End-of-Life Tires (ELTs) into usable automotive components, tailored to Zimbabwe's socio-industrial context. A mixed-methods design was employed to first map ELT flows within Harare and then experimentally assess pyrolysis emissions and material performance. The study revealed that ELT management in the city is dominated by informal burning and unregulated storage, with minimal systemic reuse. Pyrolysis experiments showed that optimal material properties were achieved at 175°C for 3 hours, yielding tensile strength (~9.63 MPa) and Shore A hardness (~71.5) suitable for non-structural automotive applications. However, chemical testing showed rising VOC and PAH emissions at higher thermal intensities, presenting occupational and environmental risks unless properly mitigated. Life cycle assessments (LCAs) demonstrated that while pyrolysis is not the lowest-emission method, its performance improves substantially when integrated with renewable energy, particularly solar thermal systems making it well-suited for application in sun-rich contexts like Zimbabwe.

5.2 Conclusions

This research has demonstrated that pyrolysis offers a viable, technically sound, and contextually appropriate solution for recycling End-of-Life Tires (ELTs) in Zimbabwe, particularly in urban settings such as Harare where unmanaged tyre waste poses growing environmental and public health risks. The lifecycle mapping exercise revealed that Harare's current ELT management system is fragmented and inefficient, characterized by widespread informal dumping, open-air burning, and uncoordinated storage by commercial actors. These practices not only contribute to pollution but also represent missed opportunities for material recovery and industrial reuse.

Experimental findings confirmed that pyrolysis, when conducted under controlled thermal conditions specifically at 175°C for 3 hours produces rubber composites with mechanical properties suitable for non-load-bearing automotive applications. The tensile strength and hardness achieved in this setting fall within international standards, supporting the feasibility of integrating such materials into Zimbabwe's automotive and light manufacturing industries. Furthermore, the addition of natural sisal fiber enhanced the structural performance of the composites while contributing to material sustainability, given its biodegradability and local availability.

However, the research also showed that pyrolysis is not without environmental consequences. As processing temperature and duration increase, so too do emissions of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), many of which exceed safe exposure thresholds if not properly managed. This underscores the need for adequate emissions control infrastructure and monitoring protocols as a prerequisite for the safe implementation of pyrolysis-based recycling systems.

Another key conclusion is that the environmental efficacy of pyrolysis is highly dependent on the source of energy used in the process. When powered by grid electricity from coal-heavy energy systems as is common in Zimbabwe pyrolysis does not always outperform mechanical grinding in terms of carbon emissions. However, when integrated with solar thermal energy systems, the emissions profile improves dramatically, making pyrolysis one of the more sustainable tyre recovery options available. This situational dependency on energy inputs suggests that pyrolysis is best suited for deployment in regions with high solar availability and energy insecurity conditions that characterize much of sub-Saharan Africa.

Finally, the study reveals a significant gap in policy readiness. Zimbabwe currently lacks a formal regulatory framework for ELT recycling and has no specific guidelines or standards governing pyrolysis operations. Without these institutional mechanisms, there is a risk that pyrolysis could be implemented in ways that replicate or worsen existing environmental and labor vulnerabilities. Thus, while the technical and material evidence supports the adoption of pyrolysis, successful scaling will require a holistic approach that includes policy development, energy integration, emissions control, and public-private collaboration.

5.3 Recommendations

To translate the research findings into action, the following recommendations are proposed for policy-makers, industry stakeholders, and research institutions. First, Zimbabwe should establish a national regulatory framework that recognizes pyrolysis and other ELT recovery methods as formal waste management practices, with clear licensing and emissions control protocols. Second, decentralized pyrolysis infrastructure particularly solar-powered units should be piloted in high-tyre-accumulation zones and integrated with emissions mitigation technologies to ensure safety and compliance.

Third, formal procurement partnerships should be fostered between recyclers and automotive manufacturers to mainstream the use of ELT-derived composites within Zimbabwe's manufacturing sector. Fourth, informal sector workers currently engaged in ELT handling should be formally trained and certified to ensure safe integration into the recycling value chain. Fifth, research and development support should be directed toward improving product formulations and expanding the range of recycled applications. Lastly, incentives for renewable energy integration and awareness campaigns should be introduced to support the environmental and social viability of ELT pyrolysis at scale.

5.4 Areas for Future Research

While this study provides a solid foundation for understanding the feasibility of pyrolysis-based ELT recycling in Zimbabwe, several important research gaps remain. Future research should focus on optimizing pyrolysis parameters by experimenting with alternative catalysts, energy-saving techniques, and additive formulations. There is also a pressing need for detailed techno-economic modeling to assess the cost-effectiveness and scalability of pyrolysis plants across different regions and production scales.

Furthermore, long-term studies should be undertaken to evaluate the health impacts of pyrolysis emissions on workers and surrounding communities, particularly in informal or unregulated environments. Researchers should also explore new applications for ELT-derived composites in sectors such as construction, transport infrastructure, and energy systems. Finally, simulationbased policy studies could help design effective regulatory frameworks and financial incentives to promote sustainable tyre recovery nationally and across sub-Saharan Africa.

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