CONTENTS

Note from the Editor's Desk 2

List of Patron Members 4

List of Fellow Members 5

Tyre Manufacturing Process Cost Reduction and Productivity Improvement through Operational Excellence. 14

The Science of Pigments: Evolution, Structure, Optical Metrics and Sustainability Challenges 17

Effect of Mastication Time on the Curing and Dynamic Properties of Natural Rubber Gum Compounds: Towards Sustainable Rubber Processing 24

From Data to Decisions: Control Charts as a Quality Compass 28

Employee Safety Awareness in a Leading Glove Manufacturing Company in Sri Lanka: Survey-Based in Sri Lanka 33

Shaping the Future of Plastics in Sri Lanka 40

Effect of Recovered Carbon Black on the Physicomechanical Properties and Curing Characteristics of Rubber Compounds 47

Rubber Resilience Under Pressure: The Strategic Fallout of SVAT Abolition and the Uncertain Promise of the Risk-Based Refund System 51

Cost-Effective Automated Plastic Sorting Using InGaAs Photodetectors and Machine Learning: A Multi-Attribute Detection Approach for Enhanced Recycling Automation 58

A review on functional Role and Advancements of Tire Plies in Pneumatic Tires 63

Innovative Model (Crown-Cone-Star) for Empowerment of Workforce 66

Emerging trend in tile industry: SPC tiles 70

A Review of Blooming in Natural Rubber Products: Mechanisms, Challenges, and Solutions 73

Developing Clear Career Pathways for the Rubber and Plastics Sector Workforce in Sri Lanka 77

A Materials Science-Based Evaluation of Pet Bottle Recycling: Structural Degradation Analysis Via Ftir Spectroscopy and Shore D Hardness Testing 81

The Modern Laboratory as a Socio-Technical System: Leadership, Quality, and Innovation in Practice. 85

Pushing boundaries! - VESTENAMER® in Recycling Rubber Applications 90

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Note from the Editor's Desk



Innovating for a Sustainable Future: Advancement in Plastics & Rubber Industry in Sri Lanka

The Plastics and Rubber Institute of Sri Lanka (PRISL) proudly presents this edition of the PRISL Journal, released under the timely and forward-looking theme "Innovating for a Sustainable Future: Advancement in Plastics & Rubber Industry in Sri Lanka."

This year's publication holds special significance. It brings together a diverse collection of research papers presented at the Plastics & Rubber Industry Research Symposium (PRIRS) 2025, alongside technical and industrial articles contributed by professionals and organizations from across the country. Together, these contributions reflect the collective strength of Sri Lanka's polymer sector — where academic research, industrial experience, and professional innovation converge to address the challenges and opportunities of a rapidly evolving world.

The plastics and rubber sectors, though often viewed through the lens of environmental concern, remain indispensable to modern life — powering essential applications in transport, healthcare, construction, packaging, and beyond. The challenge today is not about abandoning these materials, but rather about transforming the way we produce, use, and recover them. This calls for bold innovation, research-based transformation, and an ecosystem-wide commitment to sustainable practices.

Across the globe, the polymer industry is experiencing rapid technological convergence — integrating smart manufacturing, bio-based materials, digital twins, and AI-enabled quality systems. Sri Lanka's industry must adapt and evolve within this landscape to maintain competitiveness. PRISL, through its academic programs, technical seminars, and research symposia, remains dedicated to empowering professionals with the competencies required to lead this transformation.

The PRIRS 2025 Symposium once again demonstrated PRISL's pivotal role as a platform for intellectual exchange and industry collaboration. The research papers featured in this issue present advancements in materials, product development, process optimization, and circular economy practices — each contributing to the creation of a more sustainable and innovative industrial future.

Equally significant are the nationally sourced industrial and technical articles included in this issue. These contributions, written by experienced practitioners and organizations within the plastics and rubber manufacturing sectors, provide practical insights, operational strategies, and real-world perspectives. Their inclusion bridges the gap between theory and application, reinforcing PRISL's vision of uniting research with industry practice for national advancement.

At a time when industries worldwide are embracing digital transformation and sustainability-driven innovation, Sri Lanka's polymer sector must continue to invest in modernization, knowledge, and skill development. This is not merely a matter of competitiveness—it is an imperative for survival and long-term relevance in a global marketplace that rewards innovation and responsibility in equal measure.

The contents of this Journal reflect that collective journey: a journey of transformation, collaboration, and resilience. It demonstrates that sustainability in the plastics and rubber industries is not a distant ideal but a process already underway—driven by visionaries, researchers, and industry leaders working together to create positive change.

On behalf of the Editorial Board, I extend sincere appreciation to all authors, reviewers, industry partners, and contributors for their invaluable efforts in making this publication a success. Your contributions strengthen not only the intellectual foundation of our profession but also its capacity to adapt and lead in the era of sustainability.

Let this Journal serve as both a record of our progress and a call to action — to continue advancing, innovating, and collaborating in pursuit of a more sustainable and globally competitive plastics and rubber industry for Sri Lanka.

Dr. Navodi Mekhala Hakmanage

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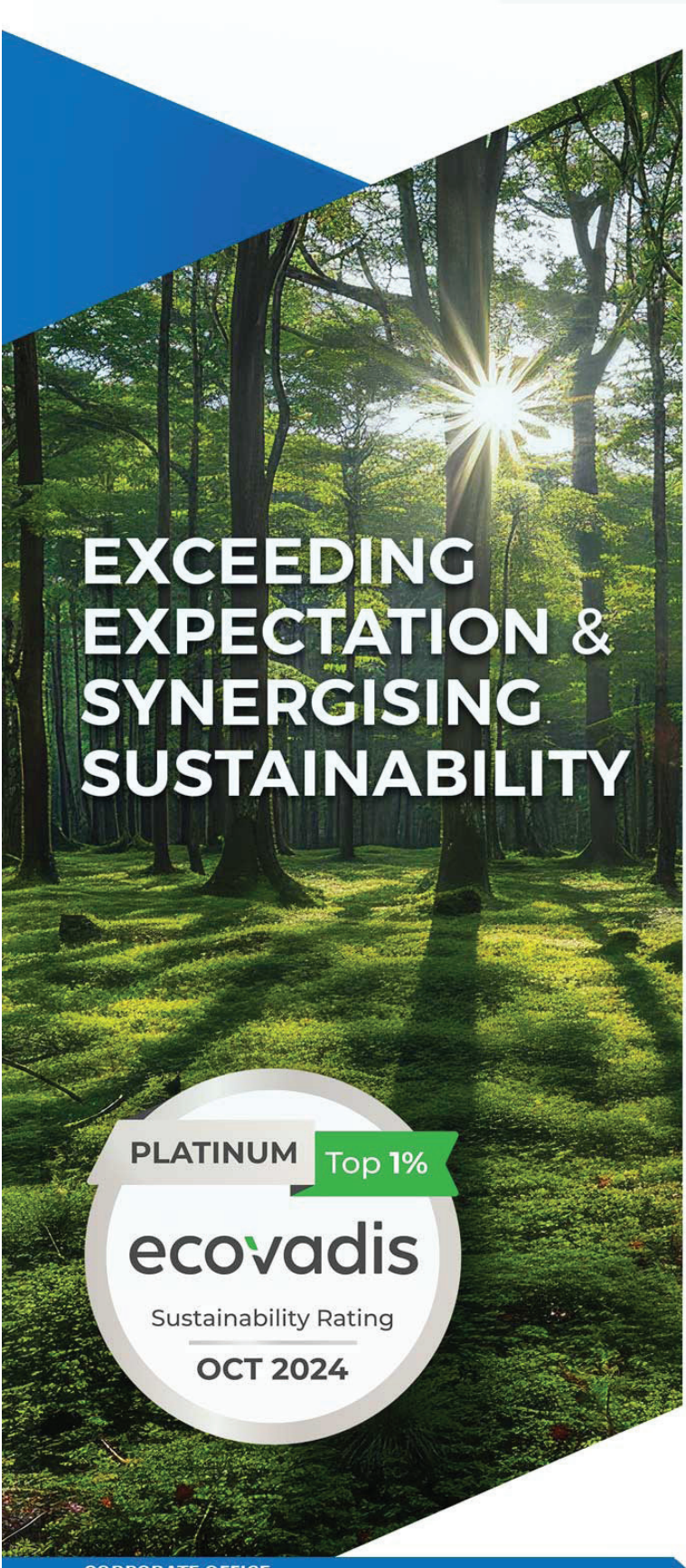
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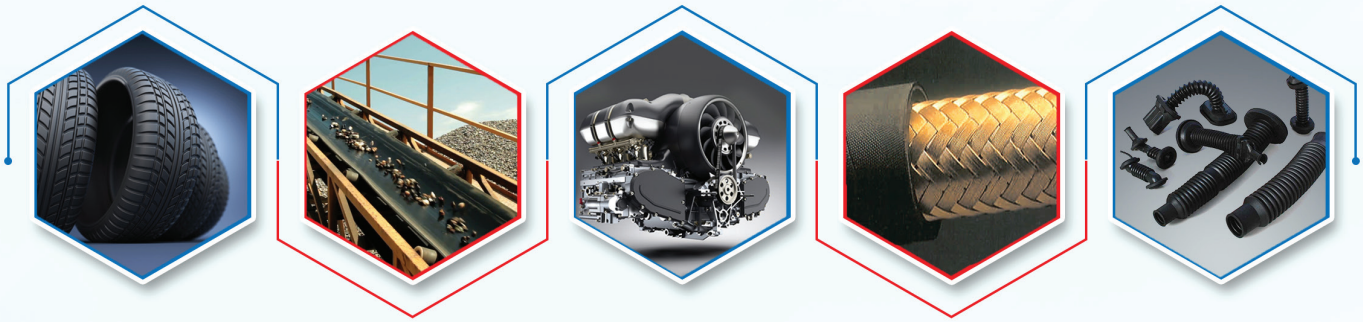
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Tyre Manufacturing Process Cost Reduction and Productivity Improvement through Operational Excellence

Dr. Udayakantha Sabaratne

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Former Senior Executive Director, Camso Loadstar
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Abstract

The tyre manufacturing industry operates within an increasingly competitive global environment where cost efficiency, productivity, and sustainability are critical success factors. Rising raw material and energy costs, technological advancements, and customer demands for quality and environmental responsibility necessitate innovative operational strategies. Drawing from both global industry examples and personal experience in establishing the Loadstar Production System (LPS) in Sri Lanka, this paper reviews how operational excellence frameworks can be applied to achieve cost reduction and productivity improvement. It explores lean manufacturing principles, energy management, digital transformation, and workforce empowerment as drivers of efficiency. Real-world examples from leading tyre manufacturers highlight how continuous improvement initiatives have enhanced process flow, reduced waste, and improved overall equipment effectiveness. Additionally, the review considers sustainability imperatives, including recycling and energy-efficient operations, and outlines the potential of emerging technologies such as artificial intelligence, robotics, and Industry 4.0 tools. The findings reinforce operational excellence as a holistic approach to securing competitive advantage while ensuring long-term growth and environmental stewardship.

1. Introduction

Tyre manufacturing is a resource-intensive process involving compounding, mixing, building, curing, and inspection stages. Global competition and cost pressures have driven manufacturers to adopt operational excellence as a strategic tool. Operational excellence integrates lean manufacturing, advance reliability centered maintenance management, and continuous improvement methodologies to optimize cost and efficiency (George, 2003). This paper reviews how cost reduction and productivity enhancement can be achieved through practical frameworks and industry practices. From a Sri Lankan perspective, a key milestone was the establishment of the Loadstar Production System (LPS) at Camso Loadstar under my leadership. This system was developed in line with the Toyota Production System (TPS) and has been sustained as the backbone of production excellence at Camso Loadstar. Even today, the LPS (though it may operate under a different name today) continues to drive cost efficiency, defect reduction, and productivity improvements, demonstrating the long-term impact of operational excellence frameworks when embedded in corporate culture. In my experience, the real success of LPS was not only the technical alignment with TPS principles but also the cultural shift it brought. Engaging operators, supervisors, and managers in continuous improvement created a strong sense of ownership, which has been vital for sustaining results.

2. Industry Overview

Tyre demand is projected to grow steadily, with increasing adoption in emerging markets (Smithers Rapra, 2022). Key challenges include raw material volatility, energy-intensive curing processes, and labor dependency in developing economies. Global leaders like Michelin and Bridgestone are addressing these with smart factories and automation investments (Michelin, 2023).

3. Cost Reduction Strategies

Lean Manufacturing Applications: Waste elimination practices based on the Toyota Production System (Ohno, 1988) can streamline operations. Case studies,

such as Goodyear's Kaizen initiatives, report 15% reductions in cycle times (Jones et al., 2019). Energy Efficiency: Energy costs represent 10–15% of total production expenses (IEA, 2021). Solutions include high-efficiency curing presses, waste heat recovery, and renewable integration. Raw Material Optimization: Recycling rubber scraps, using devulcanized rubber, and compounding innovations reduce dependency on virgin inputs (Rane & Kiran, 2020). Automation and Digitalization: Robotics in tyre building and predictive maintenance systems enhance quality and minimize downtime (Bridgestone, 2022).

4. Productivity Improvement

Total Productive Maintenance (TPM): Increases Overall Equipment Effectiveness (OEE). Case evidence from Indian tyre plants shows OEE gains from 65% to 80% (Kumar & Sharma, 2021). Workforce Development: Training in A3 ,why -why problem-solving methods and employee suggestion systems (kaizen) foster continuous improvement. Process Standardization and Quality: ISO/TS 16949 systems and Statistical Process Control (SPC) ensure consistency and reduce variability. Smart Manufacturing Technologies: AI-driven inspections, IoT sensors, and digital twins streamline production and reduce defect rates.

5. Case Studies and Industry Experiences

Michelin: Achieved 20% energy savings since 2015 by combining lean practices with sustainability targets. Apollo Tyres (India): Implemented TPM and raised productivity by 18% (Apollo Tyres, 2022). Goodyear: Leveraged AI predictive analytics to reduce maintenance costs by 12%. Camso Loadstar (Sri Lanka): The Loadstar Production System (LPS), designed and implemented as a customized operational excellence framework, has been central to sustaining world-class tyre manufacturing standards. Inspired by TPS principles but adapted to local conditions, LPS enabled significant reductions in waste, streamlined material flows, and improved overall equipment effectiveness. Importantly, the system remains active today, proving its robustness as a long-term productivity and cost management model in the tyre industry.

Principle / Focus Area	Toyota Production System (TPS)	Loadstar Production System (LPS)
Waste Elimination	Focus on seven forms of waste (muda)	Adapted to tyre-specific wastes such as excess rubber usage and rework and other process waste
Workforce Involvement	Operators trained in standardized work	Deep engagement of operators, supervisors, and managers in kaizen while standardization
Continuous Improvement	Kaizen events driven by lean teams	Embedded culture of daily problem-solving using A3 and why-why analysis
Supply Chain	Optimized for global sourcing and JIT	Localized and globalize supply chain focus to suit Sri Lankan context
Sustainability	Efficiency and cost as primary drivers	Added emphasis on long-term sustainability, cost and energy efficiency

6. Operational Excellence Frameworks

Lean manufacturing TPS principles: Merges waste elimination with statistical quality control. Continuous Improvement (Kaizen): Empowers small, incremental changes across all levels. Balanced Scorecard and KPIs: Metrics such as energy intensity, scrap rate, and OEE support informed decision-making from small cell level to business line.

7. Sustainability and Environmental Benefits

Circular Economy: Recycling tyres into crumb rubber, superfine activated crumb powder, and energy recovery reduces waste. Carbon Neutrality Goals: Continental AG aims for net-zero production by 2050 (Continental, 2023).

8. Challenges and Limitations

High capital requirements for automation, cultural resistance to change, and supply chain vulnerabilities remain significant hurdles.

9. Future Outlook

Industry 4.0 adoption with AI, robotics, and blockchain-enabled supply chains will transform operations. Growing emphasis on ESG compliance and bio-based materials will reshape tyre production.

10. Conclusion

Operational excellence offers a comprehensive approach to cost reduction and productivity in tyre manufacturing. Integrating lean philosophy, TPM, and smart technologies enhances competitiveness while aligning with sustainability imperatives. Furthermore, the Sri Lankan experience with the Loadstar Production System (LPS) at Camso Loadstar illustrates how locally developed, TPS-inspired systems can serve as enduring models of operational excellence. LPS continues to demonstrate the sustainability of structured frameworks in delivering both cost reduction and productivity improvement, making it a benchmark for the tyre industry regionally and globally. From my perspective, one of the critical lessons is that operational excellence is as much about people and culture as it is about tools and systems. The long-term sustainability of the Loadstar Production System highlights the importance of leadership commitment and workforce involvement in making excellence a way of life, not just a project.

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The Science of Pigments: Evolution, Structure, Optical Metrics and Sustainability Challenges



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Abstract

Pigments are the foundation of human creativity and discovery which bring color to our art, vibrancy to our world, and functionality to industries ranging from coatings and inks to rubber and plastics. Across the ages, pigment science has evolved from natural mineral and plant sources through early synthetic inventions to modern high-performance organic and inorganic systems. Understanding pigment behavior requires analyzing both chemical structure and optical properties, including standard colorimetric parameters such as CIELAB and **ΔE**. At the same time, present challenges over toxicity, environmental discharge, and sustainability are driving new directions in pigment development, design and regulation. This article reviews the historical development, chemical classifications, structure & property relationships, colorimetric foundations, and environmental/health aspects of pigments, highlighting recent breakthroughs and future challenges.

Introduction

Color is one of the instantaneous and powerful aspects of visual experience. In human societies, colored surfaces, paintings, textiles, prints, plastics & rubber products, toys, serve aesthetic, communicative and functional roles. At the chemical level, pigments are insoluble colorants that scatter or absorb light in selective regions of the visible spectrum, imparting hue to a substrate without dissolving in it.

Chemistry, materials science, optics, and environmental engineering are all combined in the multidisciplinary field of pigment science. In recent decades, the expansion of synthetic organic pigments, especially high-performance product categories have transformed many industries, while regulatory and ecological pressures have stimulated a shift toward safer, more sustainable options.

This article traces the development of pigment technology, investigates at chemical classes and optical metrics, explains how crystalline and molecular structure control pigment behavior, and discusses health and environmental concerns in the production and use of pigments.

Dyes vs Pigments

Despite frequently being grouped together, dyes and pigments exhibit significant differences.

The main areas of difference between dyes and pigments are their solubility and pigmentation techniques. Because dyes are soluble in water or other solvents, they can color materials by absorbing molecules throughout the medium. Pigments, on the other hand, are insoluble particles that use light scattering and surface absorption to produce color. While pigments usually stay more stable within a system, dyes can migrate, bleed, or leach due to their solubility. When it comes to optical performance, dyes offer brighter transparency and finer detail, particularly in applications such as textiles and printing inks, while pigments typically offer greater opacity, hiding power, and durability. But sometimes it's difficult to differentiate the difference between dyes & pigments, like azo pigments which are made from dye chemistry while more recent hybrid or functional pigments might contain soluble components. This interplay between soluble and particulate colorants is increasingly leveraged in advanced formulations to achieve specific optical and functional properties (Alegbe et al., 2024).

Historical Development of Pigments

Natural Origins

In art, ceramics, and decoration, ancient people uses organic materials (plants, insects) and naturally occurring minerals (such as carbon black, ochres, iron oxides, and ultramarine from lapis lazuli) as pigments. Some ancient pigments have remained stable over centuries,

as evidenced by their durability (such as Egyptian blue and specific mineral oxides).Early Synthetic Pigments

The first synthetic pigments developed in the 18th and 19th centuries. Prussian blue (iron ferrocyanide complex), which was created around 1706 was one significant example. Another is the creation of lead chromate, also known as "chrome yellow," in the early 1800s and its use in paints for artists (chrome yellow is actually lead chromate, $PbCrO_4$). Compared to nature alone, these provided richer and more distinct hues.

Industrial Revolution and Synthetic Pigment Expansion

Industrialization led to the production of pigments on an immense scale. Synthetic organics originated when coal-tar chemistry expanded. Pigments like carbon black, titanium dioxide, cadmium pigments, and other synthetic organic types started to be produced in massive quantities. Another competitive advantage was the capacity to design pigments with certain qualities (particle size, fastness, and hue).

Modern Advances

In the late 20th and early 21st centuries, advanced high-performance pigments (HPPs) became prominent. These include derivatives from diketopyrrolopyrrole (DPP), perylene, isoindolinone, and other classes offering exceptional weathering resistance and chromatic purity. There is also growing interest in organic–inorganic hybrid pigments (e.g. dyes immobilized on coatings or layered hosts) to improve stability (Marzec et al., 2019). Meanwhile, computational and machine learning methods are beginning to assist design of pigments with desired optical and stability properties (Mao et al., 2025).

Chemical Classification and Properties

Pigments are commonly classified into inorganic, organic and Chrome pigment classes, with further subdivisions by chemical family.

Inorganic Pigments

Inorganic pigments are mineral-based compounds primarily composed of metal oxides, hydroxides, sulfides, or mixed oxides. They exhibit high thermal and chemical stability, excellent opacity, and strong light-scattering properties due to their refractive indices and crystalline structures (Buxbaum and Pfaff, 2005; Eastaugh et al., 2008). Unlike organic pigments, their coloration arises from electronic transitions within metal ions rather than extended conjugated π-systems, which generally results in less vibrant hues and a muted color appearance (Herbst and Hunger, 2004; Pfaff, 2008). The reduced chromatic intensity is attributed to the limited light absorption bands of transition-metal compounds compared with the broader and more intense absorption of organic chromophores (Hunger, 2003).

Examples

- Titanium Dioxide (Pigment White 6): Exhibits a high refractive index, brilliant whiteness, and excellent hiding power; widely used in paints, plastics, and cosmetics (Faust and Aly, 1998).
- Iron Oxides (Pigment Red 101, Yellow 42, Black 11): Provide red, yellow, and brown hues with outstanding weather and UV resistance; frequently applied in construction materials and protective coatings (Sharma et al., 2015).
- Chromium(III) Oxide (Pigment Green 17): Chemically inert and heat-resistant, suitable for ceramics and industrial paints (Pfaff, 2008).
- Cadmium Sulfide (Yellow 37): Brilliant yellow with high thermal stability; use restricted due to toxicity concerns (Hunger, 2003).
- Cobalt Aluminate (Pigment Blue 28): A stable, intense blue pigment employed in automotive and architectural coatings (Pfaff and Reynders, 2017).

Inorganic pigments remain vital components in coatings, plastics, rubber and construction materials for their durability and opacity, although increasing environmental regulations promote the adoption of safer, eco-friendly alternatives (Sharma et al., 2015).

Chrome (lead chromate–based) pigments represent a historically significant group of inorganic colorants, widely utilized for their vivid hues and exceptional opacity in paints, plastics, and artists' materials during the 19th and early 20th centuries (Herbst and Hunger, 2004). The most common forms include Chrome Yellow (Lead Chromate, $PbCrO_4$; CI Pigment Yellow 34), Molybdate Orange (Lead Chromate molybdate sulfate; CI Pigment Red 104), and Chrome Green (a mixture of Lead Chromate and Chromium (III) Oxide; CI Pigment Green 15) (Pfaff, 2008; Buxbaum and Pfaff, 2005). These pigments were once valued for their intense coloration, high covering power and good weather resistance.

However, chrome pigments associated significant environmental and health hazards due to the presence of

lead (Pb) and hexavalent chromium (Cr^{6+}) compounds. Lead is a potent neurotoxin that can cause developmental and neurological disorders while hexavalent chromium is a recognized carcinogen and environmental contaminant that bioaccumulates in ecosystems (IARC, 2012; Singh et al., 2019). As a result, the production and use of these pigments have been strictly regulated or banned in most regions, triggering substitution with safer organic or mixed-metal oxide alternatives (Hunger, 2003).

Organic Pigments

Organic pigments are made up of carbon-based chromophoric structures, typically featuring conjugated π-electron systems. Unlike dyes, they are intentionally rendered insoluble either through molecular modification (such as substitution or extended conjugation) or by incorporation into host matrices. The organic class offers a broader chromatic palette, including vivid reds, blues, and greens, along with greater structural tunability. However, these advantages often come with compromises in thermal and photochemical stability. The principal categories are outlined below

1. Azo Pigments

Azo pigments are the largest class of synthetic organic pigments. They contain one or more azo groups (–N=N–) linking aromatic rings. They exhibit colors ranging from yellow through red to brown. Subtypes include monoazo, disazo, naphthol, benzimidazolone, and metal-complex azo pigments. They are widely used because of affordability and versatility. However, some degrade under heat to produce aromatic amines, potentially carcinogenic (e.g. diarylide yellows degrade to 3,3′-dichlorobenzidine) or even form inadvertent PCBs (iPCBs) in pigment manufacture (Nestler, 2019).

Subtypes:

- Monoazo Pigments
  - Example: Pigment Yellow 1, Pigment Red 3, Pigment Red 112
  - Widely used for Printing inks, plastics, coatings
- Disazo Pigments
  - Example: Pigment Yellow 12, Pigment Yellow 14
  - High tinting strength, moderate lightfastness
- Naphthol AS Pigments
  - Example: Pigment Red 57:1, Pigment Red 170
  - Brilliant reds used in plastics, paints, inks
- **β-Naphthol (Bon** Arylide) Pigments
  - Example: Pigment Yellow 74
  - Widely used for its bright yellow hue
- Benzimidazolone Pigments
  - Example: Pigment Yellow 151, Pigment Orange 36, Pigment Red 176
  - Excellent light and solvent fastness, good for high-performance coatings
- Metal Complex Azo Pigments (Chelated Azo)
  - Example: Pigment Brown 23
  - Contain coordination with metals (Ni, Cu, Cr) for improved fastness

2. Phthalocyanine Pigments

Phthalocyanines are copper-based macrocyclic pigments known for their vivid blue (PB15) and green (PG7) hues. Their planar structure and metal coordination provide exceptional stability, lightfastness, and color strength, making them ideal for high-performance applications such as coatings, plastics, and printing inks (Savastano, 2020).

Examples:

- Pigment Blue 15, 15:1, 15:2,15:3,15:4 (Copper Phthalocyanine Blue)
- Pigment Green 7, 36 (Chlorinated Phthalocyanines)

3. Quinacridone Pigments

Quinacridones are valued for their vivid red-to-violet hues and excellent lightfastness. They are widely used in high-end paints and automotive coatings.

Examples: Pigment Violet 19, Pigment Red 122, Pigment Red 202

4. Anthraquinone Pigments

Anthraquinone pigments produced red, violet and blue shades with excellent lightfastness, weather resistance, and strong chroma, making them ideal for automotive finishes, industrial coatings and plastic applications.

Examples: Pigment Red 177, Pigment Violet 43

5. Diketopyrrolopyrrole (DPP) Pigments

DPP pigments are among the most powerful modern pigments, providing brilliant red-orange hues with very high chroma, exceptional lightfastness, thermal stability, and durability, making them suitable for automotive

coatings, plastics, rubber and high-performance paints.

Examples: Pigment Red 254, Pigment Orange 73

6. Perylene and Perinones

These pigments produce deep red and orange tones characterized by high durability and vivid coloration resulting from their extended conjugated molecular structures, which enable strong light absorption. They exhibit excellent weather resistance and outstanding color brilliance, maintaining stability under prolonged exposure to sunlight and environmental conditions. Because of these properties, they are widely applied in exterior coatings, automotive paints, and high-performance rubber/plastic applications.

Examples: Pigment Red 179, Pigment Orange 43, Pigment Violet 29, Pigment Red 194

7. Isoindolinone and Isoindoline Pigments

These pigments produce bright yellow and orange tones with good chroma and solvent resistance, making them suitable for coatings, printing inks, and plastics.

Examples: Pigment Yellow 109, Pigment Yellow 139, Pigment Orange 61

8. Indanthrone and Related Pigments

These pigments are deep, stable blues with excellent heat and light stability, making them ideal for automotive and industrial coatings as well as plastics.

Examples: Pigment Blue 60 (Indanthrone Blue)

9. Condensation and High-Performance Pigments (HPPs)

This group includes quinophthalone and other specialized, condensation-derived pigments. They are designed for extreme applications (UV, chemical resistance).

Example:

- Quinophthalone (Pigment Yellow 138)
- DPP, Isoindolinone, and Perylene derivatives

10. Other Notable Classes

Other useful pigment classes include thioindigo, acridone, dioxazine, and others. Some pigments are hybrids or composites combining organic chromophores with inorganic supports for added stability (Randhawa et al., 2024).

- Thioindigo Pigments (e.g., Pigment Red 88, Pigment Violet 38)
- Acridone Pigments (e.g., Pigment Violet 23)
- Azomethine Pigments (e.g., Pigment Yellow 150)

Structure–Property Relationships

The performance of a pigment including its hue, chroma, lightfastness, chemical stability, dispersibility and hiding power is closely linked to its molecular and crystalline structure.

Conjugation and chromophore design play a critical role as the position, extent, and substituents on conjugated π systems determine absorption maxima. Electron-donating or electron-withdrawing groups can shift both hue and intensity, enabling fine-tuning of color properties (Fryer, 1997).

Polymorphism is another important factor. many pigments exist in multiple crystal forms, and variations in crystal packing can alter absorption and scattering behavior due to subtle electronic or intermolecular interactions (Fryer, 1997).

Particle size and morphology strongly influence scattering properties and hiding power. Particles that are too small relative to the wavelength of light may reduce opacity, while overly large particles can lead to settling or surface roughness.

Aggregation and crystallinity affect pigment stability and color strength. Highly crystalline pigments with well-defined domains typically exhibit strong absorption and resistance to photodegradation, whereas amorphous or disordered forms degrade more readily (Marzec et al., 2019).

Intermolecular interactions and stabilization, including hydrogen bonding, π–π stacking, coordination to metal centers, or embedding in inert matrices (e.g., inorganic hosts), further protect pigments against photochemical and thermal attack (Marzec et al., 2019). Hybrid or composite approaches, such as immobilizing organic chromophores on inorganic hosts or layered materials, enhance thermal and photochemical stability and solvent resistance without compromising hue.

Finally, electronic structure and optical transitions govern absorption wavelengths and intensities. The energies of frontier molecular orbitals (HOMO and LUMO) and electron delocalization determine color properties, and computational methods increasingly enable the prediction of pigment colors from first principles (Tomczak et al., 2013).

Understanding these structure & property relationships enables rational design of pigments with tailored hue, strength, and durability.

Colorimetric Parameters of Pigments

A major challenge in pigment science is repeatable & reproducible color assessment. To achieve this, the *CIE 1976 (Lab) color space** which commonly known as CIELAB together with the color difference (ΔE) metrics serves as the international standard for color evaluation and quality control (CIE, 1978; Hunt and Pointer, 2011).

CIE 1976 (L*a*b*) Color Space – CIELAB

The CIELAB color space, developed by the International Commission on Illumination (CIE) in 1976, represents color numerically using three parameters: L* for lightness, a* for the red–green axis, and b* for the yellow–blue axis. The system was designed to be *approximately perceptually uniform*, meaning that equal changes in coordinate values correspond to similar perceptual differences (CIE, 1978).

CIELAB describes color in three coordinates:

- L* (lightness) from 0 (black) to 100 (white)
- a* (red–green axis)
- b* (yellow–blue axis)

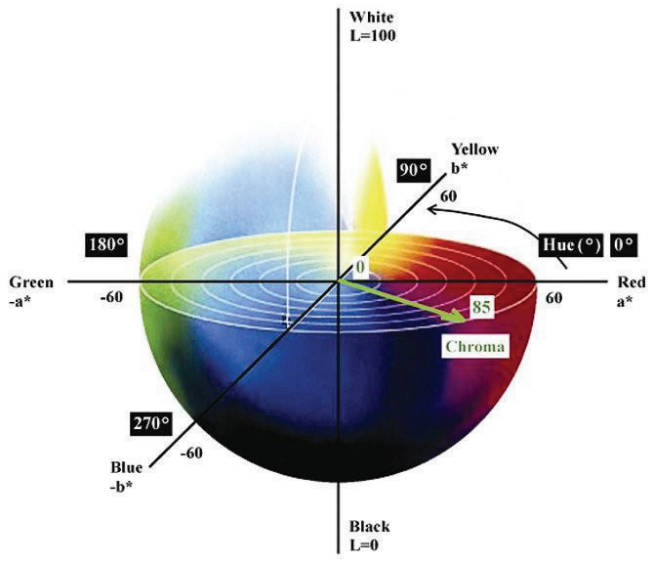


*Image 01: The three-dimensional CIE L*a*b* color space*

Conversion from CIE XYZ tristimulus values (X, Y, Z) to L*, a*, b* involves non-linear transformations based on a standard white reference point, typically illuminant D65, and functions designed to reflect human visual nonlinearity (Fairchild, 2013). Once these coordinates are obtained, chroma ($C^* = \sqrt{(a^2 + b^2)}$) and *hue angle* ($h° = arctan(b/a)$)** can be calculated to describe color intensity and tone.

Color Difference (ΔE)

The color difference (ΔE) quantifies the perceived difference between two colors in the CIELAB space. The original CIE76 formula defines this as the Euclidean distance between two color points (Robertson, 1977)

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Although simple, ΔE* has perceptual limitations, particularly for low-chroma or near-neutral colors. To address this, subsequent refinements introduced weighting factors and perceptual corrections:

In industrial practice, ΔE is widely used for color tolerance assessment. Typical thresholds as follows.

- $\Delta E \leq 1$:The color difference is nearly imperceptible to the human eye
- $\Delta E \leq 2$:The difference is slight and noticeable under controlled lighting conditions.
- $\Delta E \leq 3$:The difference is clearly noticeable and outside of industry standards (Sharma, 2017)

Overall, the CIELAB color system and ΔE metrics provide a robust quantitative framework for assessing pigment color, ensuring consistency and precision across formulation, production, and quality control processes.

Environmental and Health Considerations

Due to the extensive and worldwide usage of pigments, there are serious environmental and health consequences associated with the manufacturing process, use, and disposal. These concerns have driven stricter regulatory frameworks and extensive research toward developing safer and more sustainable alternatives.

Toxic Metals and Substitution Efforts

Many traditional inorganic pigments, such as lead chromates and cadmium sulfides, incorporate heavy metals that are toxic, carcinogenic, and bioaccumulative (Tomczak et al., 2013). Lead chromate pigments (e.g., Chrome Yellow, $PbCrO_4$) contain both lead and hexavalent chromium, making them highly hazardous and subject to severe restrictions or bans in most jurisdictions (European Chemicals Agency, 2023). Similarly, cadmium-based pigments (e.g., Cadmium Yellow, CdS) are restricted under the European Union's REACH Regulation due to their persistence and toxicity (ECHA, 2023).

These regulatory pressures have accelerated the substitution of hazardous pigments with environmental friendly alternatives, including organic pigments, rare-earth oxides, and non-toxic metal-based pigments (Randhawa et al., 2024). Additionally, manufacturing processes for certain azo and diarylide pigments can inadvertently generate toxic by-products, including inadvertent polychlorinated biphenyls (iPCBs) and 3,3′-dichlorobenzidine, a known human carcinogen (Shin et al., 2010; Washington State Department of Ecology, 2015).

Environmental Legislation

Regulatory measures governing pigment and dye industries have become increasingly stringent. In the United States, the Environmental Protection Agency (EPA) designates certain pigment production wastes particularly from azo, anthraquinone, and triaromatic pigment classes as hazardous under the K181 listing (US EPA, 2005). In the European Union, the REACH framework enforces restrictions on substances with proven toxicity or environmental persistence, including azo colorants capable of degrading into banned aromatic amines (European Commission, 2020).

Within the textile and dyeing sectors, effluent discharge regulations impose limits on chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS) and heavy metal content. These measures aim to mitigate water pollution and ecological damage (Shindhal et al., 2020). Studies indicate that regulatory enforcement has significantly improved wastewater quality while encouraging cleaner technologies and process optimization (Ghaly et al., 2014).

Effluent and Waste Management

Pigment and dye manufacturing often generate heavily colored effluents containing organic compounds, metal ions, and prolonged intermediates. Conventional treatment technologies such as coagulation, flocculation, adsorption, biological degradation, and advanced oxidation are widely used but can be limited by the complexity and toxicity of pigment effluents (Al-Tohamy et al., 2022). As a result, industries are moving toward zero-liquid discharge (ZLD) and closed-loop recycling systems to minimize wastewater generation and maximize resource recovery.

Solid wastes, particularly pigment sludge can concentrate toxic metals and organic residues, necessitating safe disposal or stabilization through solidification or encapsulation (Savastano, 2020). Increasingly, hybrid approaches combining chemical, biological, and photocatalytic treatments are being adopted to achieve higher degradation efficiency and lower environmental impact.

Shift to Sustainable Manufacturing

In response to regulatory and community pressures, pigment manufacturers are transitioning toward sustainable production models. Key strategies include:

- Development of bio-derived or renewable pigments from microbial or plant-based sources.
- Implementation of green synthesis routes using non-toxic reagents, minimal solvents and energy-efficient conditions.
- Recycling and reclamation of pigment residues and process intermediates.
- Encapsulation and immobilization techniques to reduce pigment leachability and enhance environmental safety.
- Conducting lifecycle assessments (LCA) to evaluate and minimize environmental impact.
- Ensuring supply chain transparency to prevent contamination with iPCBs or restricted substances (Nestler, 2019).

Recent innovations in pigment chemistry emphasize non-toxic metal centers, safer chromophore design and hybrid nanostructures that combine color performance with reduced environmental burden (Randhawa et al., 2024). As consumer and regulatory expectations for sustainability grow, pigment producers increasingly invest in eco-friendly formulations, renewable raw materials and closed-loop manufacturing systems (Savastano, 2020).

Conclusion

Pigments are both ancient and cutting-edge: roots in natural minerals and organic extracts and modern versions in high-performance molecular systems. Their chemical diversity ranging from inorganic oxides to advanced organic classes which provides a rich palette for applications across art, coatings, inks, plastics, rubber and beyond. Understanding pigment performance demands a firm grasp of structure & property relationships and strict quantification via colorimetric systems like CIELAB and ΔE. Yet as we continue to push pigment capability, we must equally attend to the environmental and health repercussions of pigment manufacture, use and disposal. The future of pigment science lies in balancing optical excellence

with ecological responsibility: designing stable, safe & sustainable pigments for a colorful yet healthy world.

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Effect of Mastication Time on the Curing and Dynamic Properties of Natural Rubber Gum Compounds: Towards Sustainable Rubber Processing

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Abstract

Because of the high molecular weight of NR, effective mastication of natural rubber is a fundamental prerequisite which consumes a considerable amount of energy. However, excessive mastication, can lead to degradation of the material's properties, potentially compromising final performance. Therefore, optimizing the mastication time is of great importance to ensure the energy efficiency and performance efficiency of the conversion process of natural rubber to rubber product. In this study, effect of mastication time on curing characteristics and dynamic properties of natural rubber compounds were investigated. The natural rubber compounds were masticated in an internal mixer with varying mastication time from 0 (control) to 7 minutes at six time intervals. Curing characteristics of the compounds and dynamic mechanical properties of the vulcanizates, were studied at 100 °C. It was found that curing characteristics were unaffected with the mastication time of 3 minutes, after which a delaying in both scorch time and cure time were observed. Similarly, dynamic properties of the rubber vulcanizates were also unaffected until the mastication is carried out within three minutes. It was evident from dynamic mechanical properties that possible natural rubber molecular changes are taking place as mastication time exceeds three minutes. Based on these observations, it is clear that sustainable rubber processing could be achieved through limitation of mastication for three minutes and prevention of excessive milling.

Introduction

In the case of natural rubber, being a polymer with very high average molecular weight, it is necessary to soften the rubber by the process known as "mastication". It is a fundamental and indispensable mechano-chemical process of almost all the dry natural rubber product manufacturing processes to break down high molecular weight Natural Rubber (NR) molecules into smaller fragments through mechanical means to facilitate subsequent manufacturing steps such as incorporation of other necessary ingredients and shaping (Phattarateera and Pattamaprom, 2019). It has been in practice since the invention of the masticator by Englishman Thomas Hancock in 1820 to apply a shearing force to the rubber on a two roll mill or an internal mixer. In a two roll-mill, the rolls rotate at different speeds, generating a shearing force on the rubber at the "nip" between the rolls. In an internal mixer, an eccentrically-shaped rotors apply shear force to rubber between the rotors and the walls of the mixing chamber under closed environment. While former is widely used in small scale factories, various types of internal mixers are used in large scale factories for mastication of natural rubber. Mastication using an internal mixer is energy-intensive and possible over mastication in the process adversely affects in achieving certain properties. In the context of rapid growing concerns of sustainable manufacturing approaches, lowering energy consumption and doing away with the usage of auxiliary chemicals are highly encouraged (Saidura and Mekhilef,2010). Despite limited work available in the literature focused on the effect of mastication time on some properties of NR vulcanizate, no much work has been reported on screening the effect of mastication time at short time intervals on cure characteristics and dynamic properties particularly when mastication is carried out in preparation of gum compounds where no fillers are incorporated.

Therefore, this study was aimed at investigating the effect of varying mastication time at short intervals in an internal mixer on the curing characteristics and dynamic properties of the vulcanizates namely, loss modulus, storage modulus and Tan delta with the objective of

estimation of the best minimum mastication time for NR gum compounds as shorter mastication cycles reduce the mastication energy consumption offering a sustainable approach for the mastication process.

Materials and methods

Ribbed smoked sheet rubber (RSS) no. 02 was purchased from the local rubber auction. They were cut into approximately 2" x 2" pieces and charged into an internal mixer which uses a Banbury-type rotor and masticated at a rotor speed of 40. Temperature was maintained at 45 °C. The mixer was loaded at a fill factor of 0.75. Mastication time was varied up to 7 minutes with 1-minute increments starting from 1 minute. A sample without mastication (0 min) was also prepared as the control. All the masticated samples were compounded using the same internal mixer following a standard recipe and following mixing sequence given in the Table 1. All the samples collected at the end of the first half of mixing cycle were cut into small strips and mixed again at room temperature (30°C) for 10 rounds for approximately 2 minutes on a two roll-mill keeping the nip at 3 mm. These rubber sheets were used for the second stage compounding for two minutes. Curing characteristics of the compounds and dynamic mechanical properties of the vulcanizates at 100 °C were tested using a Rubber Process Analyzer (D-RPA 3000-Mon Tech, Germany). Dynamic properties were studied at three frequencies at 0.1, 1 and 10 Hz.

Table 1: Rubber formulation used

Compound	Phr
Ribbed Smoked Sheet (RSS)	100
Zinc Oxide	4
Stearic acid	2
N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine) (6PPD)	2
Sulphur	1.8
N-tert-butyl-2-benzothiazolesulfenamide (TBBS)	1.5
N-(cyclohexylthio)phthalimide (PVI)	0.2

Results and Discussion

Table 2: Cure characteristics of rubber gum vulcanizates prepared by rubber masticated at different mastication times

Mastication time (min)	ML	MH	MH-ML	TS2	T90	CRI
0 (Control)	1.46	8.46	7.4	3.51	7.65	13.56
1	1.09	9.24	8.15	4.48	9.01	12.26
2	1.27	9.03	7.76	4.28	8.18	12.87
3	1.10	9.05	7.98	4.48	8.97	12.57
5	1.29	8.79	7.5	3.63	7.32	13.32
7	0.92	9.02	8.1	6.03	11.62	12.33

Table 2 summarizes the curing characteristics of gum compounds that were subjected to varying mastication duration. The minimum torque (ML), indicative of the viscosity of un-cross-linked rubber and thus the processability, exhibited no significant variation across the mastication times investigated. Theoretically, ML is expected to decrease with prolonged mastication due to the breakdown of long-chain macromolecules and associated chain entanglements until it reaches a limited value. However, the results observed for compounds masticated within a short time range (1 to 7 minutes) suggest minimal effect of time duration on macromolecular breakdown during brief mastication cycles.

In contrast, both the maximum torque (MH)—reflecting the stiffness of the cured compounds—and the torque difference (MH − ML) which indicates the total crosslink density of the vulcanizate, showed only a slight upward trend. This may be attributed to the limited formation of macromolecular radicals that promote crosslinking reactions. Given the low extent of radical formation, the corresponding increase in crosslink density remains modest.

Furthermore, the crosslinking rate indices of the rubber compounds were largely unaffected by short mastication durations. Although enhanced reactivity of shorter macromolecules with increased reactive ends associated with improved dispersion of curing ingredients results in reduction of both scorch time (TS2) and optimum cure time (T90), experimental data revealed no significant changes in either of the parameters up to five minutes' mastication cycle. This observation is in agreement with the results reported by Nabil et al, who studied the effect of mastication time in a wide range of tensile properties of rubber vulcanizates. The results reported by them indicate that there is no significant influence of mastication time on scorch time and cure time (Nabil *et. al 2020).* This stability may stem from insignificant effect of limited macromolecular free radicals formed and associated heat buildup during short mastication periods.

However, it is interesting to note that, as the mastication time exceeds five minutes, scorch time and cure time have been extended at a notable extent contrary to the typical expectations. The work reported by Hayeemasae et. al also have observed a *slight increase* of above parameters when mastication is increased beyond 5 minutes (Hayeemasae et al., 2021) Excessive chain **scission** reducing the **number of available double bonds and possible interference of** inactive or side reaction products formed such as epoxides, peroxides and hydroxyl containing products during excessive mastication time with curatives or crosslink intermediates may results in delay in the crosslinking process. This would be an added disadvantage of excessive mastication in addition to the high energy consumption and poor performance of the final product.

Table 3: Dynamic mechanical properties of the rubber vulcanizates prepared using different mastication times

Mastication time (min)	Frequency (Hz)								
	0.1			1			10		
	Storage modulus (kPa)	Loss modulus (kPa)	Tan δ	Storage modulus (kPa)	Loss modulus (kPa)	Tan δ	Storage modulus (kPa)	Loss modulus (kPa)	Tan δ
0	39.68	35.64	0.90	111.14	53.44	0.48	198.68	61.10	0.31
1	39.05	35.53	0.91	109.34	53.12	0.49	196.29	60.67	0.31
3	39.03	35.64	0.91	109.57	52.97	0.48	196.35	59.98	0.31
5	48.85	39.12	0.80	123.04	53.62	0.43	210.12	59.70	0.28

The dynamic property results presented in Table 3 indicate that mastication time has slightly reduced the storage modulus compared to that of the control measured at all three frequencies used in this study. This observation reflects the slight chain scission, which is not sufficient to significantly affect elasticity at a sizable level. Storage modulus which represents the **elastic (energy-storing)** portion of a material's response to dynamic deformation expected to decrease with increasing mastication time due to the breakdown of rubber molecules and molecular entanglements. Further, it is shown that beyond one-minute mastication, no significant impact observed on the storage modulus unless mastication time exceeds three minutes, after which there is an increase in the storage modulus. Formation of crystallites using oriented or aligned molecular chains during excessive mastication may be responsible for this behaviour (Choi,2000). With regard to the loss modulus which measures the **viscous (energy-dissipating)** behavior of the rubber, **non-responsive behavior of the loss modulus (E″)** to **mastication time** of the rubber compounds could be seen from the results presented in the Table 3. Loss modules depends more on **segmental motion** and **free volume**, which may not change drastically unless mastication is extreme. Tan delta values, which reflects heat energy dissipation, remains constant during the first three minutes of mastication, decreases thereafter contrary to the general trend, suggesting decreasing loss modulus, i.e. lowering viscosity with mastication (more than 3 minutes). Huang et al. has reported that, for *unfilled natural rubber (NR),* both **storage modulus (G′)** and **loss modulus (G″)** decreased dramatically that with increased mastication time (Huang, 2019). Therefore, when the rate of reduction of storage modulus surpasses the reduction of loss modulus, lowering of Tan δ could be expected. Variation of Internal molecular structure such as loss of entanglements and formation of crystalline structures may lead to the reduction of Tan δ values with excessive mastication time

Conclusions

Effect of mastication time of natural rubber at relatively small time intervals on curing properties and dynamic properties were studied. The results showed that responses of natural rubber to the excessive mastication deviate from the standard trends showing the importance of determination of optimum mastication time, even within the short mastication cycles. It could be concluded from this study that gum compounds masticated for short durations, a mastication time of just 1 to 3 minutes yields comparable curing properties along with prevention of destruction of internal natural rubber molecular structure. Therefore, this finding suggests that limiting of the mastication time of natural rubber compounds to 1–3 minutes particularly when mastication is carried out in an internal mixer leads to conserving energy and retention of properties at desired levels contributing to sustainable manufacturing practices.

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From Data to Decisions: Control Charts as a Quality Compass



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Abstract

In today's competitive industries, consistent quality and customer satisfaction are critical. Statistical Process Control (SPC) provides a practical way to manage variation, and control charts are one of its most powerful tools. This paper reviews their development, types, and uses in real-world settings. Control charts are grouped into variable charts () and attribute charts , helping companies distinguish between normal variation and serious process issues. Case studies show their benefits: in manufacturing, charts detect machine wear early to reduce downtime, while in healthcare, p-charts improve monitoring of infection rates. By offering real-time feedback, they prevent costly problems and guide corrective action. Control charts also support continuous improvement methods like Lean, Six Sigma, and TQM. With Industry 4.0, their integration with IoT and predictive analytics is expanding, making them a modern "quality compass" that helps businesses stay efficient, reliable, and competitive.

1. Introduction

1.1 Quality improvement

Quality has always been a fundamental aspect of products and services. In industrial settings, it goes beyond physical characteristics to encompass factors ensuring products or services meet or exceed customer expectations, comply with standards, and maintain consistent performance.

Quality Improvement (QI) is a systematic approach aimed at enhancing processes, products, and services to improve efficiency, effectiveness, and customer satisfaction. It emphasizes improving systems rather than blaming individuals, using data-driven, incremental changes for sustainable results. Emerging from the manufacturing sector in the 1940s, QI is also known as Continuous Quality Improvement (CQI) due to its focus on continuous learning and betterment (Langley et al., 2009).

Garvin (1987) identified eight dimensions of quality; performance, reliability, durability, serviceability, aesthetics, features, perceived quality, and conformance to standards, which provide a comprehensive framework for evaluating product quality (Montgomery, 2020).

1.2 Use of Control Charts in Statistical Process Control

Control charts, introduced by Walter A. Shewhart in the 1920s, are a fundamental tool in Statistical Process Control (SPC). They distinguish between common-cause variation, inherent in any process, and special-cause variation, which results from external or assignable factors (Montgomery, 2020). By plotting process data against statistically derived control limits, control charts provide a visual means to monitor stability, detect deviations, and ensure process consistency.

Different types of control charts are applied based on data type and process requirements. (Evans & Lindsay, 2021). These charts deliver real-time feedback, guiding decision-making by indicating whether corrective action is needed, while also preventing unnecessary responses to normal variation.

In modern industries, control charts remain central to quality frameworks such as Lean, Six Sigma, and Total Quality Management (TQM). They support root cause analysis, reduce waste, and enhance efficiency by keeping processes in statistical control (Antony, 2019).

1.3 Objectives

The main objective of this study is to examine the role of control charts in Statistical Process Control as a practical tool for monitoring, analyzing, and improving industrial processes, enabling data-driven decision-making and enhanced quality outcomes.

The specific objectives are to;

1. review the historical development, theoretical foundation, and different types of control charts within the framework of SPC.

2. analyze the role of control charts in distinguishing between common-cause and special-cause variation, and in maintaining process stability.

3. evaluate the contribution of control charts to continuous improvement and modern quality management practices such as Lean, Six Sigma, and TQM.

1.4 Significance of the Study

Control charts, first introduced by Walter A. Shewhart in the 1920s, are a core tool in SPC. They distinguish between common-cause variation, inherent in processes, and special-cause variation from external or assignable factors (Montgomery, 2020). By plotting data against statistical control limits, they provide a visual method to monitor stability and detect deviations. Different charts suit different data types and these tools deliver real-time feedback, ensuring corrective action targets genuine issues without overreacting to natural variation. Their adaptability across industries and integration with digital technologies make them essential for predictive quality management.

2. Literature Review

2.1 Evolution of Statistical Process Control in Industry

Statistical Process Control has evolved over nearly a century, growing from a simple manufacturing tool into a comprehensive quality improvement methodology applicable across various industries. Its evolution reflects a broader shift in organizational thinking about quality, moving from inspection-based approaches to data-driven prevention and continuous improvement (Montgomery, 2020; Pressbooks, 2024).

2.1.1 Origins: Shewhart and the Birth of SPC

The origins of SPC trace back to the early 1920s, when Walter A. Shewhart at Bell Telephone Laboratories developed the concept of the control chart, a tool designed to distinguish between common-cause (natural) variation and special-cause (assignable) variation in manufacturing processes. This innovation marked the formal beginning of modern quality control. Shewhart's work culminated in his landmark book, *Economic Control of Quality of Manufactured Product* (1931), which established the theoretical foundation of SPC.

2.1.2 Expansion During and After World War II

SPC gained prominence during World War II, as the demand for reliable, high-volume production of munitions and other materials drove industries to adopt systematic quality control practices. W. Edwards Deming, who worked with U.S. industries during the war, later introduced SPC and broader quality improvement principles to Japanese industries during the Allied Occupation. Japan's rapid embrace of SPC became a cornerstone of its post-war industrial success and global competitiveness.

2.1.3 Mid-to-Late 20th Century: Integration and Diversification

During the 1950s and 1960s, SPC evolved alongside TQM, reliability engineering, and experimental design. Initially used in chemical manufacturing, SPC techniques later spread to other industries to enhance process optimization, improve product reliability, and reduce defects. By the 1970s and 1980s, Japanese manufacturers, having fully embraced SPC and continuous improvement philosophies outperformed many Western firms, particularly in the automotive sector. This prompted USA and European companies to adopt SPC aggressively to regain competitiveness.

2.1.4 Modern Developments and Applications

In recent decades, SPC has expanded beyond manufacturing into service sectors such as healthcare, banking, and logistics. It is now used to monitor service delivery, identify inefficiencies, and enhance customer satisfaction. The integration of SPC with advanced technologies, such as real-time data analytics, Industry 4.0, and Six Sigma, has transformed it into a dynamic tool for proactive decision-making and operational excellence.

2.2 Practical Applications of Control Charts in SPC

Different types of control charts are applied depending on the data type and industry context. For instance, $\bar{X}$ and R charts are widely used in manufacturing to monitor critical dimensions such as diameter, weight, or thickness, ensuring that variability stays within acceptable limits (Montgomery, 2020). A study by Gijo and Scaria (2014) applied $\bar{X}$ and R charts in a textile manufacturing process to monitor yarn strength, identifying special-cause variations caused by machine maintenance issues. Similarly, p-charts are often used in service industries to track defect rates or nonconformance percentages. For example, Costa et al. (2019) employed p-charts to monitor defective transaction rates in a banking process, which helped reduce errors by 25% after corrective actions were implemented.

Control charts have also been applied in healthcare and food industries, highlighting their versatility. Woodall and Montgomery (2014) reviewed applications of control charts in healthcare, where c-charts and u-charts

were used to monitor adverse patient events and infection rates. These charts helped differentiate between normal fluctuations and unusual spikes requiring intervention. In another example, Antony et al. (2019) demonstrated the use of attribute control charts in a food packaging plant to monitor seal integrity defects. The outcomes showed significant improvement in defect detection rates, reducing customer complaints and warranty claims. Such studies emphasize that the selection of the right control chart depends not only on the type of data variable versus attribute but also on the operational context and quality objectives of the organization.

3. Methodology

3.1 Phases of the Study

This study adopts a descriptive and analytical methodology to examine the role of control charts in Statistical Process Control (SPC) and their application to industrial quality management. The approach is primarily qualitative, supported by theoretical and empirical evidence drawn from existing studies, standards, and case-based applications in manufacturing and service industries.

The methodology involves three stages. First, a literature review is conducted to trace the historical development of control charts and their theoretical foundations within SPC. This step includes reviewing classical works, as well as contemporary studies that integrate SPC with modern quality frameworks.

Second, the study provides a comparative analysis of control charts used for both variable and attribute data. The distinction between common-cause and special-cause variation is emphasized to demonstrate how control charts support process monitoring and stability assessment.

Finally, the research evaluates the contribution of control charts to continuous improvement and modern quality management practices such as Lean, Six Sigma, and TQM. Case evidence from industrial studies is used to highlight outcomes related to defect reduction, cost savings, and improved process capability.

3.2 Statistical Process Control and Control Charts

SPC is based on the principle that all processes exhibit some level of natural variation. It distinguishes between:

1. Common Cause Variation – Random, inherent variation in a process that is always present.

2. Special Cause Variation – Non-random variation resulting from external factors, signaling that the process is out of statistical control and requires corrective action.

Control charts are versatile statistical tools that are used to monitor, control, and improve processes by identifying and addressing variation.

Different charts are used depending on the type of data (variable vs. attribute) and the subgrouping of samples. Data that can be measured on a continuous scale and expressed in decimal values are called variable type or continuous data. They are Quantitative, precise, and allows for fine measurements. $\bar{X}$ and R Chart for small subgroup Size and $\bar{X}$ and S Chart for larger samples are variable type control charts (Montgomery, 2020).

Data that is counted rather than measured are called attribute type. It represents categories, pass/fail decisions, or counts of defects. This type is qualitative or quantitative, but always whole numbers (discrete). This type includes p-chart, np-chart , c-chart and u-charts (Juran & Godfrey,1999).

Table 1 compares the different types of control charts and their use in different scenarios. Each chart is described with its statistical basis, equations, and conditions of use.

4. Results

4.1 Historical Development and Types of Control Charts

The review of literature under section 2 highlights that control charts, first introduced by Walter A. Shewhart in the 1920s, have evolved from simple tools for monitoring manufacturing processes to sophisticated quality management instruments used across industries. Early applications primarily focused on $\bar{X}$ and R charts for monitoring averages and ranges of product dimensions. Over time, specialized charts such as p, np, c, and u charts were developed to handle attribute data and defect counts (Montgomery, 2020). More recent studies demonstrate the integration of advanced variations, such as exponentially weighted moving average (EWMA) and cumulative sum (CUSUM) charts, which provide greater sensitivity to small process shifts (Khoo & Wu, 2008). This historical progression illustrates how control charts remain adaptable and relevant for modern industries facing increasingly complex quality challenges.

4.2 Role in Distinguishing Variations and Maintaining Process Stability

Findings from reviewed studies emphasize the central

Table1 : Comparison of Control Charts

Chart Type	Statistic Used	Data Type	Purpose	Equation for Center Line (CL)	Example Use
X̄ and R Chart	$\bar{X}$ = subgroup mean; R = range (max − min)	Variable (measurements)	Monitor process mean and variation for small subgroups (n ≤ 10)	$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$, X_i- measurement $R = X_{max} - X_{min}$	Monitoring bottle fill weights (subgroup of 5 bottles)
X̄ and S Chart	$\bar{X}$ = subgroup mean; S = standard deviation	Variable (measurements)	Monitor process mean and variation for larger subgroups (n > 10)	$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}$	Tracking machine part diameters (subgroup of 20 parts)
p-Chart	p = proportion of defectives	Attribute (defective or not)	Monitor proportion of defectives in varying sample sizes	$\bar{p} = \frac{Defectives}{Sample\ size}$	Percentage of faulty bulbs in a lot
np-Chart	np = number of defectives in a sample.	Attribute (defective / non-defective).	Monitor the number of defective units in a sample of constant size.	$\bar{p} = \frac{Total\ Defectives}{Total\ inspected}$ $CL = n \cdot \bar{p}$	Inspecting 100 circuit boards per shift and recording defective items.
c-Chart	c = number of defects per unit	Attribute (defects counted)	Monitor number of defects when sample size is constant	$\bar{c} = Average\ no.of\ defects\ per\ unit$	Scratches per car door
u-Chart	u = average defects per unit	Attribute (defects counted)	Monitor number of defects when sample size varies	$\bar{u} = \frac{Defects}{Units\ inspected}$	Defects per 100 meters of fabric

role of control charts in differentiating between common-cause and special-cause variation. In manufacturing environments, for example, X̄-R charts have been used to detect machine wear and operator-related errors, reducing unplanned downtime and increasing productivity (Yang & El-Haik, 2009). In healthcare applications, p-charts monitoring infection rates allowed managers to identify unusual spikes attributable to external causes, prompting timely corrective actions (Thor et al., 2007). These results show that control charts not only ensure stability but also provide a visual and statistical basis for intervention, which helps organizations avoid costly defects and maintain consistent performance.

4.3 Contribution to Continuous Improvement and Modern Quality Practices

The findings also confirm that control charts are integral to broader quality management frameworks such as Lean, Six Sigma, and TQM. For instance, several Six Sigma projects report significant defect reductions when control charts were incorporated into the "Control" phase of the DMAIC cycle (Pyzdek & Keller, 2014). In the automotive industry, the use of CUSUM charts was shown to support continuous monitoring of critical safety components, directly improving customer satisfaction and compliance with international quality standards (Singh & Khanduja, 2012). Such evidence highlights that control charts not only help maintain short-term stability but also contribute to sustained long-term process improvement, making them indispensable in competitive industrial settings.

4.4 Role of Control Charts in SPC

The role of Control Charts in SPC with the main stages is briefly outlined as follows.

1. Process Data Collection - Measurements of quality characteristics (e.g., dimensions, defect counts, error rates).

2. Plot on Control Chart - Data points compared against Center Line (CL), Upper Control Limit (UCL), Lower Control Limit (LCL).

3. Variation Analysis

   - If points fall within limits, common-cause variation (process stable).

   - If points fall outside limits or show non-random patterns, special-cause variation (process unstable).

4. Decision & Action

   - For common-cause, maintain process, monitor continuously.

   - For special-cause, investigate root cause, implement corrective action.

5. Continuous Improvement - Feedback loop to Lean, Six Sigma, or TQM practices.

5. Conclusion

This study examined the role of control charts in Statistical Process Control (SPC), highlighting their historical evolution, methodological foundations, and practical significance across industrial sectors. The findings confirm that control charts are not only

essential for differentiating between common-cause and special-cause variations but also for maintaining long-term process stability. Their ability to provide real-time insights ensures that industries can take timely corrective actions, thereby preventing defects, reducing waste, and sustaining operational efficiency.

Furthermore, the review emphasizes that control charts remain highly relevant in contemporary quality management frameworks such as Lean, Six Sigma, and TQM. Their integration with modern digital technologies also strengthens their applicability for predictive quality management, aligning with Industry 4.0 initiatives. By functioning as a "quality compass," control charts enable organizations to move from reactive approaches to proactive and preventive strategies, ensuring sustainable competitiveness in both manufacturing and service industries.

Overall, the study concludes that control charts are indispensable tools in quality improvement, serving not only as monitoring instruments but also as catalysts for continuous improvement and long-term organizational excellence.

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Employee Safety Awareness in a Leading Glove Manufacturing Company in Sri Lanka: Survey-Based in Sri Lanka



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Abstract

This study analyzes occupational safety awareness in a prominent glove production company using a survey-based assessment of workers' knowledge, systematic ability, and safety culture. Substantial compliance levels, with over 90% knowledge in safety training, emergency communication, and essential equipment awareness. Employees also reflected confidence in managing medical emergencies. However, major deficiencies were identified: 20.75% had confusion in selecting appropriate extinguishers, and proactive hazard control was weak, as only 3.77% focused alerting co-workers. perceived hazard varied, with the Chemical Handling Safety module receiving lowest instructional priority despite frequent operational use. These gaps highlight the need for obligatory practice-based training to strengthen critical skills such as response to electrical hazards. The study further recommends adopting a Just Culture framework to reinforce safety as an organizational priority.

1.0 Introduction

Employee safety is essential to occupational health and production. Workers are frequently exposed to accidents, injuries, and occupational illnesses in the apparel industry, construction sector, manufacturing plants, and healthcare occupations. But as major challenges, we can see lapses in regulatory compliance and limited safety awareness among workers in spite of Occupational Safety and Health (OSH) regulations, such as the Factories Ordinance and the Department of Labor regulations. including the National Institute of Occupational Safety and Health (NIOSH) Act, No. 38 of 2009 [MA2]. Specifically, in developing countries, strengthening knowledge, setting up and maintaining a culture of safety is essential for minimizing hazards in working environments and complying with global labor standards.

1.1 Background and Context

The garment and rubber industries, including glove manufacturing, are key to the country's economy and employ the majority of the workforce. Glove production carries multiple risks, including chemical exposure (latex or nitrile), machinery hazards, repetitive strain, and fire from combustible materials. Safety is therefore a critical necessity, not just a regulatory formality. Despite laws like the Factories Ordinance, enforcement and employee adherence remain challenging. This study examines a leading Sri Lankan glove manufacturer to assess shop-floor workers' safety awareness and identify existing gaps.

1.2 Aims & Objectives

The purpose of this study is to investigate the level of workplace safety in Sri Lanka and study factors about behaviors in safety.

Objectives:

1. To assess the employees' knowledge and attitudes about workplace safety.
2. To evaluate the level of training and communication provided by companies.
3. To identify barriers among employees regarding safety awareness.
4. To propose applications to improve the safety awareness of employees and to develop a safety culture.

1.3 Significance and scope of the study

Improved safety consciousness minimizes accidents, absenteeism, and improves efficiency. The study aids organizational leaders and stakeholders in implementing targeted training and promoting safety practices. Focusing on the employees of a glove manufacturing company, it prioritizes safety awareness and attitudes above operational risk control. The results are applicable to Sri Lanka and other economies in the developing countries.

2.0 Literature Survey: Employee Safety in Material-Based Industries

2.1 Accidents and Hazards in Material-Based Manufacturing

Rubber, plastics, and textiles are material-processing industries with high hazards. Injuries are often caused by mechanical (machinery contact, pinching), chemical (solvent or corrosive exposure), or physical (noise, heat, handling stress) hazards. Low safety awareness and poor risk assessment also lead to increased frequencies of accidents. Sri Lankan studies (Kahatapitiya et al., 2022) show common machine operation, material handling, and chemical exposure occurrences, which suggest local safety shortcomings.

2.2 Specific OSH Challenges in the Glove Manufacturing Sub-sector

Glove production, as a niche branch of the rubber industry, involves serious OSH risks like exposure to gas and chemicals, latex sensitization, and repetitive work-induced musculoskeletal diseases. Aggregated rates of work with additional international supply pressures compound these risks (Hasle & Jensen, 2012; Kumara & Jayawardena, 2018). In addition, rubber and chemical combustibility necessitates rigorous fire protection training.

2.3 The Link between Awareness, Training Efficacy, and Safety Culture

Accident prevention is dependent on the proficiency of employees and a proper safety culture. General industry training in all material-processing industries is not sufficient; hands-on, context-specific practical training supports wearing PPE, readiness for emergencies, and safety in general. Practical training reduces accidents, evidenced by fact (Maduranga & Harshani, 2024), and experience-based learning reinforces confidence and upholds safety routines (Reason, 1997).

3.0 Methodology

3.1 Research Design

The study applied a quantitative, illustrative research design adopting a cross-sectional survey method. This was applied to objectively determine the present status of safety awareness among the sample of workers at a particular point in time. The survey-based design is the most appropriate for measuring existing awareness, beliefs, and practices of employees concerning workplace safety.

3.2 Participants

The study engaged 53 workers from a glove factory, randomly sampled across departments (production, engineering, materials, packing) to reduce selection bias.

3.3 Procedure

Data were collected through structured, face-to-face interviews with a standard questionnaire. Interviews were employed rather than written questionnaires to transcend illiteracy issues, preserve question simplicity, and achieve complete answers. Conducted in a personal, unbiased setting, they achieved participation and minimized bias.

3.4 Analysis

All collected data, consisting of categorical (multiple-choice) variables, were evaluated through descriptive statistics. Key tools for analysis comprised:

- Frequency Distribution: Used to determine the absolute number and percentage of respondents selecting each option (e.g., ‘Yes’, ‘No’, ‘Not sure’).
- Cross-Tabulation: To analyze relationships between demographic factors (like ‘Work Experience’ or ‘Safety Training’) and critical safety awareness (like ‘Confident in Emergency’).

3.5 Ethics and Limitations

Ethical permission was received, and verbal agreement with assured confidentiality was ensured from participants. Limitations are limited sample size (N=53) and self-reported data bias.

3.6 Future Improvements

Future research could use a larger, multi-site sample and compare companies with distinct accident rates. Combining empirical observations, such as timed fire drills, with questionnaires could diminish dependence on self-reported data.

4.0 Results and Analysis

4.1 Demographic Profile of Participants

The study surveyed 53 randomly selected employees. The analysis of their demographic data provides the necessary context for interpreting the safety awareness results.

Q1. Age Group (Demographics)

Age Group	Count	Percentage	Total Responses
18-25	11	20.75%	53
26-35	17	32.08%	53
36-45	11	20.75%	53
46-55	11	20.75%	53
Above 55	3	5.66%	53

Most of the respondents (32.08%) are aged 26–35 years, followed by 18–25, 36–45, and 46–55 at 20.75% each, and above 55 at 5.66%. This relatively young labor force indicates the need for lively, simple-to-understand safety instruction.

Q2. Gender (Demographics)

Gender	Count	Percentage	Total Responses
Male	46	86.79%	53
Female	7	13.21 %	53
Prefer not to say	0	0.00%	53

The sample is heavily male-skewed (86.79% male, 13.21% female), usual of heavy manufacturing but limiting relevance, as female perspectives—especially in quality control, packing, or clerical roles—may be marginalized.

Q3. Work Experience in this company (Demographics)

Option	Count	Percentage	Total Responses
Less than 1 year	9	16.98%	53
1-5 years	14	26.42%	53
6-10 years	10	18.87%	53
More than 10 years	20	37.74%	53

The highest respondent group (37.74%) has over 10 years of experience, showing the influence of long-tenured employees on safety culture. Effective orientation is also crucial, as the "Less than 1 year" group is substantial (16.98%).

Q4. Have you received any safety training? (Training Compliance)

Option	Count	Percentage	Total Responses
1. Yes	49	92.45%	53
2. No	4	7.55%	53

A positive finding: 92.45% of employees reported having safety training, showing strong compliance, though training quality warrants further review.

Q5. Do you know where the First Aid boxes are located?

Option	Count	Percentage	Total Responses
Yes	50	94.34%	53
No	3	5.66%	53
Not sure	0	0.00%	53

First Aid box location awareness is nearly flawless at 94.34%. This shows that the company has efficiently marked and hinted at the location of its lowest medical stores, and it is crucial to quickly respond to accidents.

Q6. Do you know where the Fire Extinguishers are located?

Option	Count	Percentage	Total Responses
Yes	51	96.23%	53
No	1	1.89%	53
Not sure	1	1.89%	53

Fire Extinguisher location familiarity is high at 96.23%. This is a superior rate for general fire safety preparedness and bears witness to the clear visibility and notification of such emergency devices.

Q7. Are you aware of which fire extinguisher type is used for which kind of fire?

Option	Count	Percentage	Total Responses
1. Yes, I know	41	77.36%	53
2. I only know a little	11	20.75%	53
3. No	1	1.89%	53

While 77.36% answered with full knowledge, over 20% admit to knowing only "a little". When employed

in a glove factory environment, where there is a risk of chemical or electrical fires, the right option is critical. This wide discrepancy shows that expert, hands-on fire training on the different classes of fire and the correct usage of respective extinguishers is needed.

Q8. Do you know the emergency contact number for medical help at your workplace?

Option	Count	Percentage	Total Responses
Yes	49	92.45%	53
No	3	5.66%	53
Not sure	1	1.89%	53

A strong 92.45% of employees know the emergency contact number. This key piece of information for initiating a rapid response is well-communicated across the workforce.

Q9. If a fire breaks out, what would be your first action?

Option	Count	Percentage	Total Responses
Call the emergency number	37	69.81%	53
Use a fire extinguisher	13	24.53%	53
Run outside immediately	3	5.66%	53
Wait for instructions		0.00%	53

Most respondents (69.81%) correctly identify calling the emergency number first, ensuring professional engagement and proper alarm procedures. A smaller portion (24.53%) would use an extinguisher first, while very few consider running outside (5.66%) or waiting for instructions (0%), indicating a generally good understanding of the need for prompt action.

Q10. If a co-worker gets an electric shock, what is the first step you should take?

Option	Count	Percentage	Total Responses
1. Touch them to pull away	4	7.55%	53
2. Switch off the power before helping	40	75.47%	53
3. Call emergency medical services	8	15.09%	53
4. Do nothing until others arrive	1	1.89%	53

75.47% workers correctly identified the crucial response, “Switch off the power before helping,” indicating effective hazard-specific training. However, 7.55% chose the dangerous option, “Touch them to pull away,” indicating a critical training gap that could lead to a second injury and must be addressed.

Q11. If a co-worker has a heart attack, what would be your first response?

Option	Count	Percentage	Total Responses
Call for medical help immediately	34	64.15%	53
Start CPR if trained	9	16.98%	53
Give water and wait	1	1.89%	53
Move them to a chair	9	16.98%	53

The correct priority of “Call for medical help immediately” was selected by 64.15%. The second action to start CPR (16.98%) is correct for those who are trained. The 16.98% who would attempt to “Move them to a chair” shows a dangerously low level of knowledge of first aid, as handling a casualty improperly may lead to further harm to their condition.

Q12. If your colleague uses an inhaler/medicine and faces breathing difficulty, what should you do?

Option	Count	Percentage	Total Responses
Help them use the inhaler/ medicine	38	71.70%	53
Call a medical emergency	15	28.30%	53
Wait until they recover	0	0.00%	53
Not sure	0	0.00%	53

The responses reflect good judgment, with 71.70% being correct in choosing to "Help them use inhaler/ medicine" that addresses an immediate need to manage a diagnosed condition. The 28.30% who would simply call an emergency are also choosing a safe alternative. The **segment** reflects an awareness of both immediate aid and emergency escalation.

Q13. Do you think employees should share important medical conditions for safety?

Option	Count	Percentage	Total Responses
Yes, definitely	53	100.00%	53
Only with supervisors	0	0.00%	53
No, it's private	0	0.00%	53
Not sure	0	0.00%	53

The results show a surprising and resounding consensus: 100.00% of the respondents believe employees should "Yes, definitely" reveal major medical conditions for safety. The result strongly suggests that, at least in this sample, there seems to be an evident understanding and acceptance that safety has precedence over privacy concerns in the matter of critical medical information.

Q14. If you notice a slippery or wet floor in your department, what would you do?

Option	Count	Percentage	Total Responses
Clean/wipe immediately if safe	43	81.13%	53
Inform cleaning staff	8	15.09%	53
Warn others & place caution sign	2	3.77%	53
Ignore it	0	0.00%	53

Responses show high responsibility, with 81.13% selecting to "Clean/wipe immediately if safe" and none doing nothing. However, only 3.77% choose the optimal response, "Warn others & place caution sign." While employees act to correct hazards, training should prioritize hazard communication to prevent accidents before cleanup.

Q15. Do you feel confident to act during a medical emergency?

Option	Count	Percentage	Total Responses
1. Yes	53	100.00%	53
2. No	0	0.00%	53
3. Not sure	0	0.00%	53

Unexpectedly, 100% of respondents indicated confidence in acting during a medical emergency, showing very high self-efficacy. This depicts earlier findings but, combined with high safety training compliance (Q4), suggests effective practical training that builds staff confidence.

Q16. What kind of safety training is most important?

Option	Count	Percentage	Total Responses
Fire safety & evacuation	11	20.75%	53
First aid & CPR	10	18.87%	53
Electrical safety	3	5.66%	53
Chemical handling safety	4	7.55%	53
ALL	25	47.17%	53

A large plurality of respondents (47.17%) selected the 'all' option; it's good to see. Among the specified options, "Fire safety & evacuation" (20.75%) and "First aid & CPR" (18.87%) were most highly ranked. As the company is a glove manufacturer, the relatively low position of "Chemical handling safety" (7.55%) is of concern, as this is one of the high-risk factors for the industry.

5.0 Discussion

This section presents the quantitative results of the Employee Safety Awareness in a Leading Glove Manufacturing Company survey, categorized into three domains: Demographics, Foundational Safety Knowledge, and Procedural & Safety Culture Insights.

5.1 Demographics and Foundational Compliance

The employees are young but experienced, with the age group 26–35 constituting 31.48%, while 37.74% have over 10 years of service (Q3). Gender distribution is highly skewed, with 86.54% of the participants being male (Q2). Foundation safety compliance is high: 92.45% have received training (Q4), 94.34% are aware of the First Aid box location (Q5), 96.23% are aware of the Fire Extinguisher location (Q6), and 92.45% are aware of the emergency contact number (Q8). These findings reflect good communication and rollout of critical safety resources.

5.2 Procedural and Technical Knowledge: Strengths and Gaps

Critical Emergency Response: 75.47% correctly answered switching off power first in assisting a colleague with electric shock (Q10), reflecting effective hazard-specific training. Similarly, 69.81% ranked calling the emergency number first in case of fire (Q9), reflecting familiarity with escalation procedures.

Technical Gaps: A small but significant minority (7.55%) would touch a shock victim, showing a dangerous knowledge gap requiring urgent intervention. A further 20.75% lack detailed knowledge of fire extinguisher types (Q7), which is hazardous for their inappropriate use in a glove factory containing different combustible substances.

5.3. Safety Culture, Confidence, and Risk Perception

Confidence: 100% of the employees are confident in their ability to handle medical emergencies (Q15), indicating that training effectively translates into practical ability and self-efficacy.

Medical Privacy Consensus: 100% agreed that serious medical conditions should be revealed for safety's sake (Q13), indicating a culture that prioritizes the greater good.

Hazard Control Gaps: Only 3.77% prioritized warning others and posting caution signs for a slippery floor (Q14) first, while 81.13% opted to clean it immediately. This indicates a lack of proactive hazard communication and risk control.

Misaligned Training Priorities: Chemical safety, one of the core hazards, was prioritized first by only 7.55% of participants (Q16), which may indicate that workers are underestimating chemical hazards in relation to fire (20.75%) or First Aid (18.87%).

6.0 Conclusion and Recommendations

The company has successfully developed a very compliant group of employees with good safety foundation knowledge and high self-reported confidence. The study identifies two primary areas for strategic intervention:

6.1 Enhance High-Risk Procedural Training:

Mandate periodic, interactive reminder sessions (e.g., simulation, live demos) to reduce the minority who would be involved in unsafe behaviors (e.g., 7.55% risking electrocution) and to remind them of technical knowledge (e.g., correct fire extinguisher selection).

6.2 Enhance Proactive Safety Culture:

Shift training to proactive management of hazards and communication, specifically, the temporary hazard procedure (e.g., the three steps: Warn, Control, Report). Further, correct the low ranking of Chemical Handling Safety by better communicating the related industrial risks to align employee perception with actual workplace hazards.

6.3 Building a Culture of Shared Ownership for Safety

Apart from training and procedures, the company must develop a strong internal safety culture, where staff members consider safety as everyone's responsibility and not just rules. The "Just Culture" must promote hazard and near-miss reporting without fear of punishment. Leadership must model safe behavior daily, and frontline Safety Teams must make it possible for staff members to recognize and fix hazards such that safety becomes a daily, core value and not a formal requirement.

7.0 Acknowledgment

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Shaping the Future of Plastics in Sri Lanka

Industry Trends, Trade, and Sustainability Pathways



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1. Introduction

1.1 Purpose and scope of the article

The purpose of this article is to provide a comprehensive review of the plastics industry in Sri Lanka, assessing its size, structure, market performance, regulatory environment, and sustainability challenges. The scope is national, but with references to global developments that shape local industry dynamics. By examining trade flows, sectoral demand, policy frameworks, and technological trends, the article aims to deliver insights valuable to policymakers, businesses, and researchers concerned with industrial growth and environmental management in Sri Lanka (OECD, 2022).

1.2 Importance of industry reviews

Industry reviews are critical for aligning strategic priorities across government and industry stakeholders. For policymakers, they offer evidence for regulatory reforms, investment incentives, and environmental safeguards (UNIDO, 2020). For businesses, reviews provide strategic intelligence on raw material trends, import dependency, and consumer market shifts. For academics and researchers, they highlight areas for further exploration, such as recycling technologies, bio-based plastics, and circular economy models (Al-Salem et al., 2023). In the case of Sri Lanka, where plastics contribute significantly to domestic consumption and exports, periodic reviews help navigate between growth imperatives and sustainability demands.

1.3 Background of the plastics industry (global and Sri Lankan perspective)

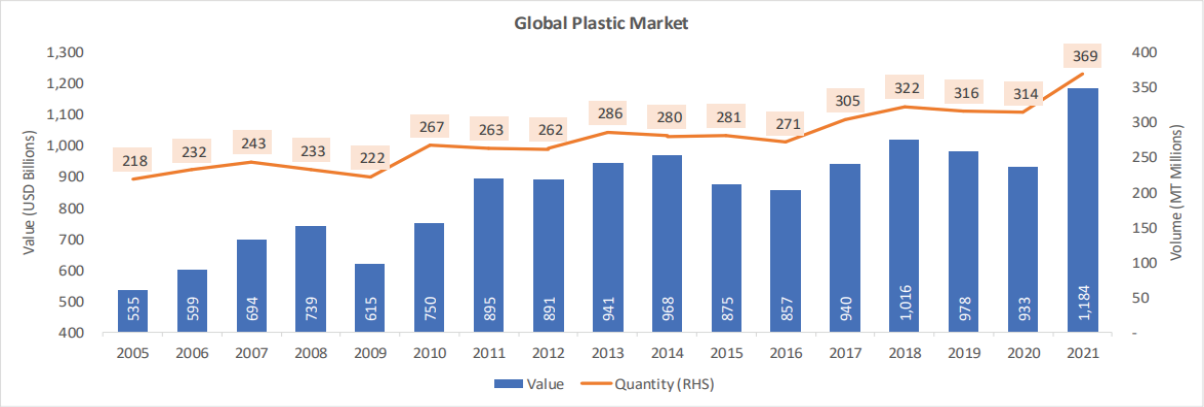
Globally, the plastics industry is valued at more than **USD 600 billion**, driven by demand in packaging, construction, healthcare, and consumer goods (Grand View Research, 2023). However, concerns over environmental sustainability, particularly waste management and single-use plastics, have accelerated regulatory and technological changes (PlasticsEurope, 2022).

Sri Lanka's plastics industry, though smaller in scale, plays a vital role in supporting local manufacturing and export capacity. More than 400 enterprises are engaged in plastic processing, supplying approximately 140,000 metric tons annually, with demand concentrated in packaging, construction, household goods, and healthcare (Sri Lanka Business, 2024). The industry is highly import-dependent for raw polymers such as polyethylene and polypropylene, yet it shows steady annual growth of 10–12% (Ministry of Industry, 2023). These features make the sector both an economic enabler and a sustainability challenge, warranting closer review.

2. Global Plastics Industry Overview

2.1 Market size, growth trends, and leading global players

The global plastics market is large and steadily expanding. In 2023 the plastics market was valued at approximately **USD 624.8 billion**, and it is forecasted to grow to about **USD 645.1 billion by 2030**, at a compound annual growth rate (CAGR) of around **4.2%** for 2024-2030 (Grand View Research, 2023). Other estimates show somewhat lower base values but similar growth trajectories; for example, Fortune Business Insights places market size at **USD 524.48 billion in 2024**, rising to **USD 754.23 billion by 2032**, implying a CAGR of approximately **5.1%** (Fortune Business Insights, 2024).



Source: UN Trade and Development (UNCTAD)

Figure 01 – Global Plastic Market growth (from 2005 to 2021)

Source – UN Trade and Development (UNCTAD)

The Asia-Pacific region dominates in both volume production and revenue share, supported by rapid industrialization, urbanization, and growing demand in sectors like packaging, construction, and household goods (Fortune Business Insights, 2024). Polyethylene (PE) leads among plastic resin types, due to its versatility and broad use in packaging and consumer product applications. Other major polymer types include polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS) (Verified Market Reports, 2025).

Major global players in the plastics sector include **SABIC, Borouge, LyondellBasell, Dow Inc., INEOS, ExxonMobil Chemical**, among others (Fortune Business Insights, 2024). These firms are influential in raw resin production, R&D of advanced plastics, and in scaling sustainability efforts due to their economies of scale and market reach.

2.2 Key technological and sustainability trends

Three linked trends are shaping the global plastics industry:

- **Circular economy & recycling**: There is growing emphasis on recycling (mechanical and chemical), reuse, and designing products for end-of-life recovery. Regulatory pressures and consumer expectations are pushing for higher recycled content in plastics and reduced reliance on virgin fossil-based resins (Fortune Business Insights, 2024).

- **Bioplastics and renewable feedstocks**: Bioplastics (derived from corn starch, sugarcane, etc.) and bio-based polymers are gaining traction, particularly for use in packaging and disposable goods, as more regions adopt mandates or incentives for biodegradable or compostable materials (Fortune Business Insights, 2024).

- **Digitalization, automation, and performance-oriented innovations**: Manufacturers are investing in process automation (e.g., robotics, IoT), advanced polymer chemistries (for lightweight, high-strength, or improved thermal/chemical resistance), and smarter manufacturing to reduce waste and enhance product quality (Grand View Research, 2023).

2.3 Global challenges: feedstock price volatility, environmental regulations, and more

Despite growth, the sector faces several serious challenges:

- **Feedstock price and supply volatility**: Most conventional plastics are derived from fossil fuels (petroleum, natural gas). Fluctuations in crude oil and gas prices, supply chain disruptions, geopolitical instability, and tightening of fossil fuel extraction standards all contribute to cost uncertainty and risk (Research and Markets, 2023).

- **Environmental regulations and policy pressure**: Many countries have introduced bans or stricter controls on single-use plastics, increased requirements for recycled content, restrictions on certain additives or plastic types, and extended producer responsibility laws. These raise compliance costs and force changes in material selection and design (Fortune Business Insights, 2024).

- **Sustainability demands and public perception**: Growing awareness about plastic pollution (especially marine plastics and microplastics), carbon emissions in plastic production, and waste management deficits pressure companies to adapt or face reputational risk (Fortune Business Insights, 2024).

- **Technological & infrastructure gaps for recycling**: Even where regulatory pressure and market demand exist, many regions lack sufficient recycling infrastructure, sorting systems, and investment in advanced recycling technologies, which limits scale and effectiveness (Verified Market Reports, 2025).

3. Sri Lankan Plastics Industry Context

3.1 Size and structure of the plastics industry

The plastics industry in Sri Lanka consists of numerous processors ranging from small workshops to larger enterprises focusing on packaging, construction materials, household goods, and industrial components (Data Book 2023). Local manufacturers engage in processes such as injection moulding, extrusion (films, sheets, pipes), thermoforming, and flexible and rigid packaging (Ministry of Industries, 2024). While exact total production tonnage for plastics alone in 2024 is not publicly documented, the industry is noted to have "significant growth" in recent years, driven by increased consumption in packaging, construction, and consumer goods sectors (Data Book 2023)

3.2 Import dependence on raw polymers

Sri Lanka remains heavily dependent on imports for raw polymer materials (virgin resins, additives, and semi-finished plastics). According to a recent market outlook, in 2023 Sri Lanka's plastic import market was **approximately. USD 852 million**, and it is projected to reach **USD 959 million** by 2028, with an average annual growth rate of about **1.9%** (ReportLinker, 2024). Meanwhile, plastic exports were around **USD 98 million** in 2023, forecasted to increase to about **USD 110 million** by 2028 (ReportLinker, 2024). These figures reflect a large disparity between import and export values, indicating that much of domestic plastic demand is met through imports (ReportLinker, 2024).

3.3 Major local players and their contributions

The Data Book (2023) indicates that many local firms are involved in packaging (films, flexible and rigid packaging), household plastics (containers, storage items), construction plastics (pipes, sheets, profiles), and industrial/consumer accessories. Some companies have also begun exploring recycled plastics and eco-friendly material alternatives in response to regulatory and market pressures (Ministry of Industries, 2024). PRISL has highlighted optimism for demand recovery in certain export markets, such as the United States, for select plastic products (Daily Mirror, 2025), which suggests export-oriented firms are active.

3.4 Sectoral demand: packaging, construction, household goods, healthcare

The strongest demand in Sri Lanka has been in **packaging**, especially flexible film and packaging for food & beverage and retail, followed by **construction** for pipes, fittings, and sheets. Household goods (storage containers, kitchenware, small appliances) remain steady consumers of plastic materials. The **healthcare** sector demand is growing but remains relatively small; for example, demand for medical disposable items and sterile packaging increased during and after the COVID-19 pandemic. There is also a rising interest in sustainable packaging among consumers and regulators, which is influencing product design and materials used.

4. Trade Dynamics and Market Performance

4.1 Import vs export performance (values, volumes, trends)

Recent data show a significant trade deficit in plastics, where imports of plastics and plastic packaging materials are much higher than exports. As noted, in 2023 imports were around **USD 852 million**, with exports at about **USD 98 million** (ReportLinker, 2024). Export growth is modest, projected to reach USD 110 million by 2028 (ReportLinker, 2024). The growth rate of import volume (or shipments) shows a rise: for instance, plastic material imports in the 12 months September 2023-August 2024 had 166 shipments, supplied by 104 foreign exporters to 55 local buyers, marking a **43% increase** in shipment count compared to the prior 12 months (Volza, 2024). This signals growing import volume.

4.2 Key trade partners

Sri Lanka imports plastic raw materials and packaging products from a variety of countries; while specific recent ranking data for all partners is limited, trade records show substantial imports of plastics from China, Korea, the UAE, India, and Southeast Asian countries (Volza, 2024). On the export side, key destinations include the European Union: in 2024, EU imports of plastics from Sri Lanka amounted to **USD 13.02 million** (Trading Economics, 2024). Also, PRISL has expressed confidence in demand in the U.S. market for select product lines, though precise share data are not publicly available (Daily Mirror, 2025).

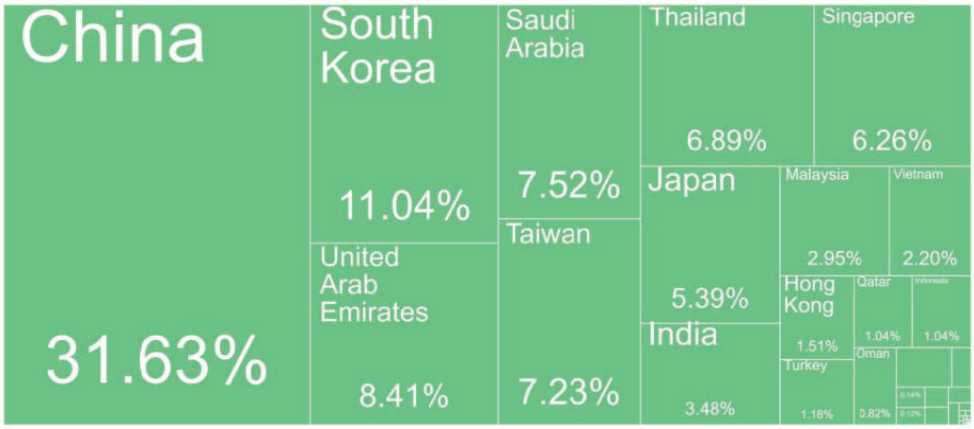


Figure 02 – Share of Plastic Imports in Southern Asia in 2023

Source – Havard of Kennedy School of Government

4.3 Regional competitiveness and opportunities

Sri Lanka's competitive advantages include its strategic location, established small to medium plastics companies with experience in packaging and flexible film production, and generally lower labor costs. Opportunities exist in increasing domestic value-addition (for example, shifting from imported films/sheets to locally produced preforms, molded plastics, or packaging solutions), leveraging trade agreements, and expanding exports to neighboring markets (India, Southeast Asia, Middle East). Growth in recycled plastics, rigid and flexible packaging innovations, and sustainable/eco-friendly materials are emerging areas of opportunity. However, scaling up requires investment in technology, quality standards, and logistics/transport infrastructure.

5. Policy, Regulation, and Institutional Framework

5.1 Government policies on plastics

Sri Lanka has begun implementing regulatory measures to control plastic waste and manage environmental impact. For instance, the National Action Plan on Plastic Waste Management (2021-2030) outlines targets and measures for waste reduction, recycling, and improved collection systems. There are bans or restrictions on selected single-use plastic items; adoption of Extended Producer Responsibility (EPR) frameworks is being explored. Policy discussions and implementation are ongoing, though enforcement in many local areas remains a challenge.

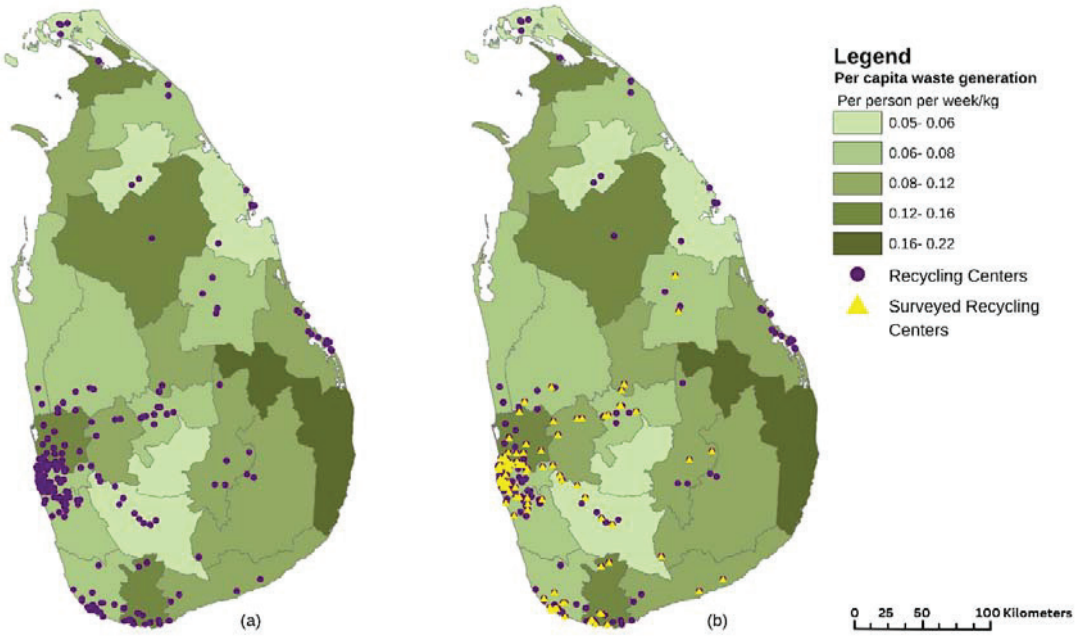


Figure 03 – Registered recycling and waste collecting centers in Sri Lanka

Source – Statistical Package for the Social Science (2024)

5.2 Industry regulations and incentives

Regulation of plastics imports and standards falls under various statutes and regulatory bodies; import licensing, material standards, and environmental controls are used to manage quality and environmental safety (Data Book 2023). Incentives for local plastic processors may include duty concessions or tax benefits when local content or processing value addition is increased (as per policy drafts and trade-promotion offerings), though detailed updated incentive schedules specific to plastics were not publicly available in the latest reports. Compliance with international packaging and export standards (e.g., for food safety, recyclable content) is becoming more important for export-oriented firms.

5.3 Role of PRISL and other associations

The Plastics & Rubber Institute of Sri Lanka (PRISL) functions as the professional body that connects industry players, provides training, technical guidance, and participates in policy dialogue. In 2025, PRISL publicly expressed optimism about demand for Sri Lankan plastics products in U.S. markets rebounding, which suggests their advocacy and market intelligence roles remain relevant (Daily Mirror, 2025). Other institutions, such as the Ministry of Industry, the Export Development Board (EDB), and environmental agencies, play regulatory, trade-promotion, and environmental oversight roles. Collaboration between the government, PRISL, the private sector, and NGOs is seen as essential to implement policies successfully.

6. Sustainability and Circular Economy Practices

Sri Lanka faces serious environmental challenges linked to plastics. The country generates over **260,000 tons** of plastic waste annually, of which around **69%** remains unmanaged — uncollected, burnt, or openly dumped (Ministry of Environment, 2024). A national plastic waste inventory confirmed that only about **3%** of plastic waste is recycled in formal systems, with the rest contributing to pollution and leakage into rivers and marine ecosystems (Jayasinghe, 2023). Mismanagement at every stage of the waste chain — collection, transport, and disposal — amplifies the problem (Balachandra & Abeysekara, 2024).

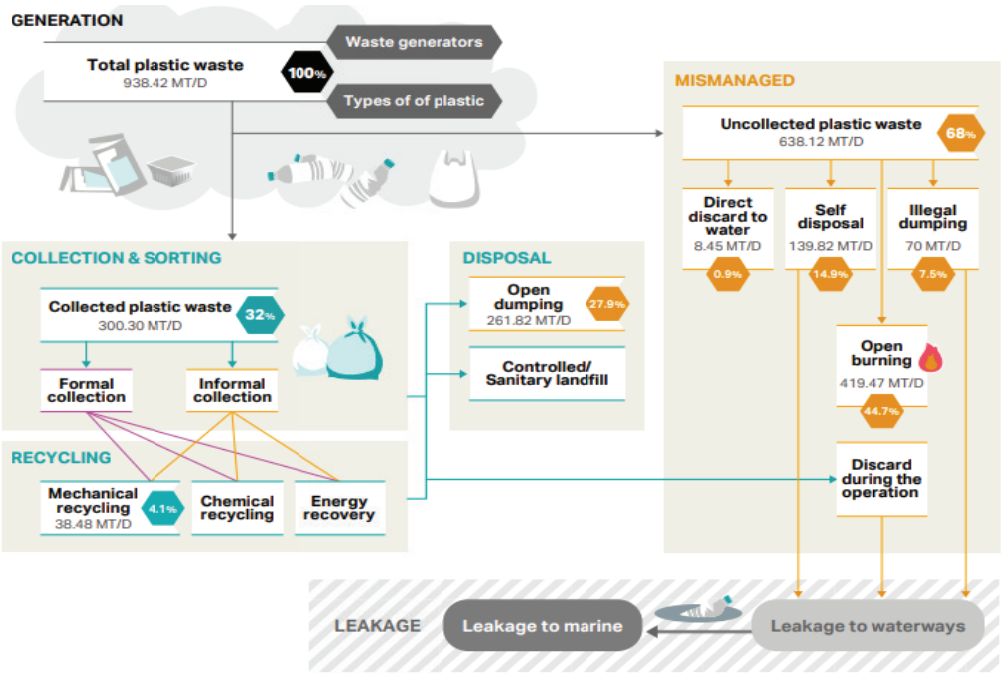


Figure 04 – Estimated Plastic Material Flow in Sri Lanka

Source – Ministry of Environment, Sri Lanka (2024)

Several initiatives have been launched to address these gaps. The **National Action Plan on Plastic Waste Management 2021–2030** provides a policy framework for reducing plastic leakage, improving collection efficiency, and scaling recycling infrastructure (SWITCH-Asia, 2024). Industry-led initiatives such as the **Plasticcycle programme** by John Keells have built community awareness and established collection points to channel plastics for recycling (Biodiversity Sri Lanka, 2024). Government agencies are also exploring **Extended Producer Responsibility (EPR)** schemes, alongside bans on selected single-use plastic products (SWITCH-Asia, 2024).

Biodegradable plastics are increasingly discussed as an alternative. The 2024 Congress for Sustainable Materials highlighted their potential in packaging, food service, and retail, though costs and lack of technical standards limit uptake (Hayleys, 2024). Green manufacturing practices are also emerging, with firms introducing

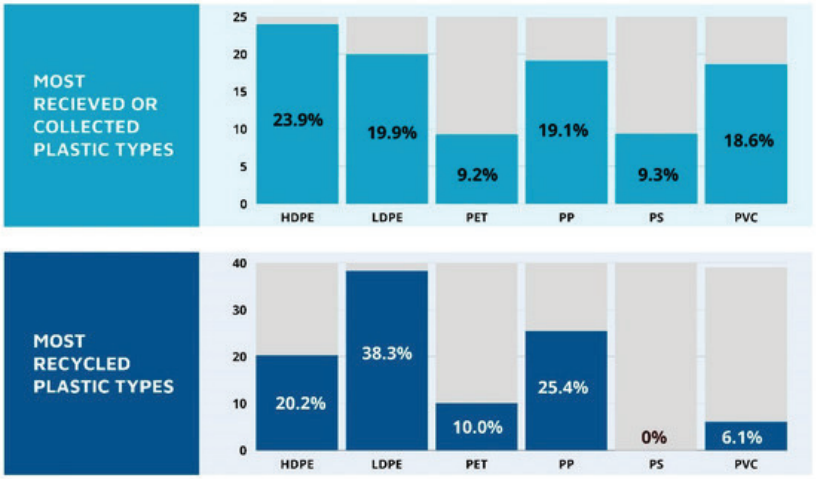


Figure 05 – Plastic collection and recycling at collection centres

Source – Statistical Package for the Social Science (2024)

energy efficiency measures such as variable frequency drives and audits to manage high energy costs (Industries Climate Response, 2025). These practices show early promise but require stronger policy support, investment, and consumer acceptance to scale effectively.

7. Challenges Facing the Sri Lankan Plastics Industry

Sri Lanka's plastics industry is highly **import-dependent**. Virgin resins and polymer intermediates are imported mainly from India, China, and other Asian markets. Consequently, global oil price fluctuations and exchange rate volatility directly influence production costs and profit margins (ReportLinker, 2024). This leaves processors vulnerable to external shocks and reduces competitiveness.

Energy and infrastructure limitations represent another critical challenge. The 2022–2023 energy crisis underscored how energy-intensive plastics processing is, and how electricity shortages or tariff hikes can raise costs sharply (Industries Climate Response, 2025). Modernizing equipment could improve efficiency, but high capital costs act as a barrier. Waste management infrastructure also remains weak — particularly in non-urban areas — which hinders recycling and circular economy development (Ministry of Environment, 2024).

Finally, **waste management and consumer perception** remain problematic. Public awareness of proper segregation and disposal is limited, and consumer willingness to pay for eco-friendly or biodegradable plastic alternatives remains low (Jayasinghe, 2023). Enforcement of single-use plastic bans is inconsistent, contributing to ongoing leakage of plastics into the environment (SWITCH-Asia, 2024). Together, these issues create a cycle of environmental harm and reputational risks for the industry.

8. Future Outlook and Opportunities

Despite challenges, the plastics industry in Sri Lanka retains strong **growth potential**. Packaging is expected to remain the largest demand sector, with growth in flexible packaging, PET bottles, and retail films (Data Book, Ministry of Industry, 2024). Construction will continue to drive demand for pipes, sheets, and roofing as infrastructure projects expand. Export opportunities exist in value-added packaging and household plastics, especially in the US and EU, where compliance with sustainability standards can provide a competitive advantage (Daily Mirror, 2025).

Digital technologies and R&D will be central to competitiveness. Adoption of automation, IoT, and predictive maintenance could reduce waste and energy intensity (Industries Climate Response, 2025). Research collaborations with universities can accelerate the development of biodegradable plastics and improved recycling technologies. Globally, investment in chemical recycling and compostable materials is increasing, and Sri Lanka can benefit by adapting these to local needs (Hayleys, 2024).

Public–private partnerships (PPPs) represent a key enabler. Recycling infrastructure — such as material recovery facilities and advanced sorting plants — requires capital beyond the capacity of most local SMEs. PPPs can fill this gap while fostering shared responsibility. Incentives such as tax breaks for recycled content, subsidies for biodegradable alternatives, and international funding for sustainability projects can further support industry transition (SWITCH-Asia, 2024). Industry associations like PRISL are positioned to connect firms with policymakers and international trade partners to align local practices with global standards (Daily Mirror, 2025).

9. Conclusion

The plastics industry in Sri Lanka is at a crossroads. On one hand, it underpins critical sectors such as packaging, construction, and consumer goods, supporting economic growth and employment. On the other hand, it contributes heavily to environmental degradation, with mismanaged waste exceeding **69%** of total plastic waste generated (Ministry of Environment, 2024). Low recycling rates, high import dependency, energy constraints, and weak waste infrastructure remain core issues.

Yet there are opportunities. National strategies such as the **Plastic Waste Management Action Plan 2021–2030**, industry-led initiatives like **Plasticcycle**, and rising interest in biodegradable plastics and green manufacturing provide momentum for change (Hayleys, 2024). To capitalize on this, Sri Lanka must strengthen regulatory enforcement, expand waste management infrastructure, invest in R&D and energy-efficient technologies, and promote PPPs for recycling and sustainable innovation.

Ultimately, aligning **policy, business, and research** is vital. If collaboration is achieved, the plastics industry can transition from being a driver of pollution to a leader in sustainable industrial development. With the right mix of incentives, investments, and consumer behaviour change, Sri Lanka's plastics industry can secure both its economic future and environmental responsibility.

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Effect of Recovered Carbon Black on the Physicomechanical Properties and Curing Characteristics of Rubber Compounds

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Abstract

This paper presents the experimental results obtained from the study on incorporating recovered Carbon Black (rCB) produced from pyrolysis process of end- of- life- tires in to a solid tire tread compound. The purpose of this study is to increase the technical knowledge on the use of rCB as a sustainable alternative for virgin carbon black (vCB). The primary objective is to contribute to environmental sustainability by reducing reliance on commercial grade- N375 CB and promoting circular economy practices within the rubber industry. The earlier studies were successfully discovered that rCB has lower reinforcement properties compared to the vCB and could not be replaced the vCB completely from the rCB. Therefore, this study evaluates the effect of recovered carbon black (rCB) on the physicomechanical properties and curing characteristics of solid tire tread compounds by replacing virgin carbon black (N375), which constitutes the novelty of the work. rCB source from Indian supplier was evaluated through the incremental addition of rCB in addition to replace the existing N375 phr level in the formulation at 5, 10, 15, and 20 phr levels. According to the results with the increment of rCB loading mechanical properties and rheological properties of the compounds lower than the vCB loaded compounds. Despite this, interesting performances can be achieved when rCB is incorporated into the formulations at 10 phr by replacing N375 load from 10 phr of rCB in the compounds. The mechanical and rheological properties of the 10 phr rCB reinforced compounds were matched with the properties expected by the 100% vCB reinforced compounds. The study concludes that rCB can serve by using a combination of rCB with conventional CB grade- N375 to obtain the optimal balance of reinforcement and targeted properties.

Keywords: Circular economy, Environmental Sustainability, Recovered Carbon Black, Tread Compound, Virgin Carbon Black,

1. Introduction

The growing global demand for tires, projected to exceed 2.9 billion units annually, poses significant environmental challenges due to the generation of approximately 17 million tons of waste tires each year (Dwivedi et al., 2020). Waste tires, composed of natural and synthetic rubbers, carbon black (CB), and additives, are resistant to degradation and difficult to recycle effectively, making waste tire management as a global concern (Dwivedi et al., 2020). Carbon black, a key reinforcing filler in rubber compounds, enhances mechanical properties, durability, and wear resistance in tires. However, traditional CB production via partial hydrocarbon combustion releases carbon dioxide and polycyclic aromatic hydrocarbons (PAHs), contributing to environmental concerns (Cardona et al., 2018). These challenges have driven interest in sustainable alternatives such as recovered carbon black (rCB) (Zhong et al., 2019).

1.1. Pyrolysis and Recovered Carbon Black (rCB)

Pyrolysis offers a promising solution to reduce tire waste and the carbon footprint of CB production. This process thermally decomposes tires in the absence of oxygen, yielding pyrolytic oil, gas, and recovered carbon black (rCB) (Dwivedi et al., 2020; Cardona et al., 2018). rCB retains many of the properties of virgin CB (vCB) but contains impurities like ash and carbonaceous deposits, which can limit its reinforcing efficiency (Dwivedi et al., 2020). Although rCB can be used as a partial or full substitute for vCB, its performance depends on the pyrolysis process and post-treatment methods (Urrego Yepes et al., 2021). Treatments like acid washing and heat treatment improve rCB's purity and surface activity, enhancing compatibility with rubber matrices (Dwivedi

et al., 2020).

1.2. Incorporating Recovered Carbon Black in Solid Tire Compounds

Solid tires, used in industrial and heavy-duty applications, demand tread compounds with high durability and wear resistance. Traditionally, vCB has been preferred due to its superior reinforcing properties (Zhong et al., 2019). However, incorporating rCB offers a sustainable alternative as the tire industry prioritizes environmental solutions. Challenges with rCB, such as lower surface area and higher ash content, can reduce its reinforcing efficiency compared to vCB. Inorganic impurities, including zinc oxide and silica, may weaken filler-rubber interactions, impacting mechanical properties like tensile strength and abrasion resistance (Dwivedi et al., 2020; Cardona et al., 2018). However, optimizing pyrolysis and post-treatment processes can improve rCB's performance, making it suitable for specific applications (Urrego Yepes et al., 2021). This study evaluates the incorporation of rCB in solid tire tread compounds, focusing on its mechanical properties, reinforcing efficiency, and environmental benefits as a sustainable alternative to (vCB), which constitutes the novelty of the work.

2. Methodology

2.1. Materials and characterization

Virgin carbon black (vCB, N375) served as a baseline for comparison, while recovered carbon black (rCB) from an Indian pyrolysis plant was evaluated in various formulations. The properties of rCB and vCB, obtained from supplier-provided Certificates of Analysis (COA), included inorganic content, pour density, oil absorption number (OAN), pellet hardness, and iodine adsorption number (IAN), as summarized in Table 1.

Table 1: Structural Properties of the rCB and vCB

Parameter	Units	rCB	vCB	Test Standard
Ash Content	%	17.57	0.5	ASTM D 1506
Pour Density	kg/ m3	475	370	ASTM D 1513
Oil Absorption Number	ml/100g	84	102	ASTM D 2414
Pellet Hardness	gf	36	29	ASTM D 5230 (vCB) ASTM D 3313 (rCB)
Iodine Adsorption Number	mg/g	NA	83.8	ASTM D 1510

Recovered carbon black (rCB) exhibits distinct differences from vCB, including higher ash content (17.57% vs. 0.5%), reflecting residual ash from the pyrolysis process (Dwivedi et al., 2020). Its lower oil absorption number (OAN, 84 vs. 102 ml/100g) indicates reduced surface activity, while higher pellet hardness (36 gf) enhances processing durability but may hinder uniform dispersion.

2.2. Formulation and preparation of composites

In this study, a series of rubber composites were formulated to assess the performance of recovered carbon black (rCB) in comparison with virgin carbon black (vCB). Five different formulations were prepared as shown in the Table 2, a control formulation (R0) containing 100% vCB (N375) as the reinforcing filler, and four experimental formulations (R5, R10, R15, and R20), In which rCB was incrementally added at 5, 10, 15, and 20 phr, respectively, by replacing vCB. All other raw materials were kept constant across formulations to ensure comparability. An industrial scale Banbury mixer was employed for mixing and preparation of rubber compounds. After mixing the compounds were sheeted out. Curing ingredients were added 24 h later in industrial scale kneader and warmed in two roll mill and molded vulcanizate sheets were prepared in two-day- light hydraulic press at 150 ◦C of vulcanization temperature.

Table 2: Formulation of Rubber Compounds

Formulation ingredients expressed in parts per hundred rubber (phr)	Compound No.				
	R0	R5	R10	R15	R20
Rubber	100	100	100	100	100
N375	47	42	37	32	27
rCB	0	5	10	15	20
Crumb rubber	6	6	6	6	6
Chemicals	8.9	8.9	8.9	8.9	8.9

2.3 Cure characteristics

The curing characteristics of the rubber compounds were evaluated using an Oscillating Disc Rheometer (ODR) at 150°C. Parameters such as minimum torque (ML), maximum torque (MH), scorch time (ts2), and optimal curing time (tc90) were recorded. ML indicates the degree of mastication, while MH-ML reflects the cross-linking density of fully vulcanized rubber. The tc90 represents the time required to achieve 90% of the cross-linking reaction, with an increase in torque signifying higher cross-link density.

2.4. Structural properties

The Specific Gravity (SG) of the compounds were measured in a Wallace density meter at 24 ◦C, in accordance with the ASTM D792 standard. The samples were first weighed in air (*m1*) and then immersed and weighed in distilled water (*m2*). The density of the distilled water ($\rho 1$) was set to 1 g/cm3. The density of the composites was recorded.

2.5. Mechanical properties

The mechanical properties of rubber compounds with recovered carbon black (rCB) were evaluated following ASTM standards. Tensile strength and elongation at break were measured using a tensile testing machine (ASTM D412) on dumbbell-shaped specimens at a 500 mm/min crosshead speed. Tear strength (ASTM D624) was assessed with crescent-shaped specimens, while modulus at 300% elongation, indicating stiffness, was recorded during tensile tests. Shore A hardness (ASTM D2240) was measured with a durometer, and abrasion resistance (ASTM D5963) was determined using a DIN Abrader by recording weight loss. All tests were performed in triplicate to ensure accuracy.

3. Results And Discussion

All characterized results are shown in the Table. 3.

3.1. Cure characteristics.

Maximum torque (MH), reflecting compound stiffness, showed minimal change around 6 dNm units through the test series. Minimum torque (ML), indicating pre-vulcanization viscosity reduces slightly incorporation with rCB. Scorch time (ts2) and cure time (tc90) increased slightly, but they are still within the acceptable limits, so rCB doesn't significantly affect the curing times.

3.2. Physical Properties

The specific gravity (SG) of the rubber compounds remained constant across all formulations.

3.3. Mechanical properties.

The performance of recovered carbon black (rCB) was evaluated against virgin carbon black (vCB, N375) using the control compound (R0) as a baseline. The key observations for mechanical properties of the tread compounds are discussed below.

3.3.1. Tear strength

Tear strength was highest in the control compound (R0) and decreased with increasing rCB loading. At 5 and 10 phr, tear strength was slightly lower but acceptable for certain applications, at 15 and 20 phr, it declined significantly due to weaker filler-polymer bonding caused by rCB's lower surface area.

3.3.2. Tensile modulus @300%, Tensile Strength, elongation at break, rebound resilience and hardness

The modulus at 300% elongation decreased with rCB loading, with R15 & R20 showing the lowest modulus but it was not larger deviation. This reflects less stiff compounds, attributed to rCB's larger particle size and reduced surface activity, though excessive stiffness may compromise flexibility and durability. Tensile strength decreased with rCB loadings compared to the control (R0). Indicating partial substitution is feasible without significant performance loss. Tensile strength declined significantly due to increased ash content and weaker filler-polymer interactions in rCB, consistent with prior studies (Dwivedi et al., 2020; Zhong et al., 2019). At 5, 10 and 15 phr, the reduction in elongation was moderate and within acceptable limits, suggesting minimal impact on flexibility. However, at 20 phr, elongation out of required limits, reflecting the increased stiffness of the compounds due to higher rCB content, which limits their ability to stretch under stress. Rebound resilience increases as more rCB is added, suggesting that replacing fully reinforcing fillers from rCB allows the polymer chains to move more freely. The hardness of the rubber compounds has remaining same through the series.

3.3.3. Abrasion Resistance

Abrasion resistance, a critical property for tire treads, declined with increasing rCB content. At 5 and 10 phr, the abrasion loss values were comparable to the control compound (R0), indicating that rCB can match vCB performance for moderate wear resistance applications. However, at 15 and 20 phr, large particle size and ash content in rCB resulted in significantly higher abrasion loss, consistent with trends observed for tensile strength and tear strength.

Table 3: Characterized results of the compounds

Parameter	Units	Compound No.				
		R0	R5	R10	R15	R20
MH	d Nm	86.31	84.22	84.4	80.47	79.88
ML	d Nm	25.36	24.76	24.76	23.7	22.35
ts_2	Seconds	408	410	414	472	473
Tc_{90}	Seconds	660	661	651	733	713
Specific Gravity	NA	1.11	1.11	1.11	1.11	1.11
Tear Strength	kg/ cm	74	73	71	65	62
Modulus at 300%	Kg/ cm2	139	139	136	131	131
Tensile Strength	Kg/ cm2	253	234	230	225	218
Elongation at Break	%	515	480	488	498	440
Hardness	Shore A	66	66	66	66	66
Rebound Resilience	%	53	54	56	57.5	59
Abrasion Loss	mm3	108	108	114	128	128

4. Conclusion

This study highlights the potential of using recovered carbon black (rCB) as a partial substitute for virgin carbon black (vCB) in solid tire tread compounds. While rCB showed comparable mechanical properties to vCB at lower loadings (up to 10 phr), higher loadings reduced reinforcement efficiency due to higher inorganic content, lower oil absorption number (OAN), and lower surface activity. These results suggest that rCB can serve as a sustainable alternative through partial replacement of virgin carbon black, contributing to a circular economy in the rubber industry. However, limitations remain in understanding rCB's reinforcing efficiency. Key factors like crosslink density and bound rubber, which influence rubber-filler interactions and vulcanization, were not evaluated in this study. Future research should address these factors and optimize pyrolysis and post-treatment processes, such as surface modification or ash removal, to enhance rCB's reinforcing potential. Overall, rCB may serve as a viable and sustainable alternative to vCB, especially at lower loadings, reducing reliance on virgin materials and promoting sustainability by reusing pyrolysis-derived materials.

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Rubber Resilience Under Pressure: The Strategic Fallout of SVAT Abolition and the Uncertain Promise of the Risk-Based Refund System



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Abstract

The recent abolition of the Suspended Value Added Tax (SVAT) scheme in Sri Lanka, replaced by a proposed risk-based refund system, has generated significant concern among rubber products manufacturers and exporters. This paper critically examines the potential operational, financial, and strategic implications of this policy shift for the rubber manufacturing value chain. Key issues include cash flow constraints, administrative inefficiencies, unequal advantages for large BOI enterprises, barriers for SMEs and new entrants, and a potential decline in sectoral competitiveness and investment attractiveness. Drawing on Strategic Choice Theory and Institutional Theory, the article analyses how these reforms influence firms' decision-making under uncertainty and highlights the structural impact on local primary producers, deemed exporters, and overall value chain dynamics. The findings underscore the need for policy coherence, institutional readiness, and digital innovation to sustain the competitiveness of Sri Lanka's rubber export sector. This concept paper proposes two potential pathways: reinstating a revised SVAT mechanism with enhanced digital monitoring or implementing a fully integrated, real-time digital VAT refund system. Both approaches aim to reconcile fiscal integrity with liquidity protection, while reinforcing the economic rationale that VAT, as a consumption-based tax, should be levied on final goods rather than intermediate production materials.

Introduction

The abolition of the Suspended Value Added Tax (SVAT) system, effective from October 1, 2025, has drawn significant opposition from exporters across Sri Lanka, particularly from the rubber products manufacturing sector. As one of the country's key export-oriented industries, rubber manufacturers and exporters actively urged the government to reconsider this decision, highlighting the potential operational and financial disruptions it could cause. Their concerns stem from the sector's vital role in sustaining foreign exchange earnings and industrial employment during a period of economic instability and recovery. Despite these appeals, the government proceeded with the repeal of the SVAT scheme and introduced a so-called "risk-based refund system" in its place. Tax regime of a country plays a vital role in shaping its national economic landscapes (Baiardi et al., 2019; Dabla-Norris et al., 2017)overall tax revenue and tax composition. We find that there is some evidence of a negative and statistically significant relationship between tax revenue and economic growth, while there are no robust relationships between revenue-neutral tax shifts and economic growth. The results hold in different samples of OECD countries for different time periods. We also identify different relationships between the short run and long run. Overall, our results cast doubts on the potential growth enhancing effects of a shift from direct to indirect taxation, with paramount consequences on tax policy.","container-title":"International Tax and Public Finance","DOI":"10.1007/s10797-018-9494-3","ISSN":"0927-5940, 1573-6970","issue":"2","journalAbbreviation":"Int Tax Public Finance","language":"en","note":"number: 2","page":"282-316","source":"DOI.org (Crossref. In economies where growth and sustainability are heavily dependent on exports, tax policy can either infuse or constrain business performance (Chen et al., 2006). This article critically examines the potential adverse effects of this policy shift on the rubber products manufacturing and export supply chain, assesses its broader implications for the national economy, and explores possible strategies that industry stakeholders can adopt to mitigate the emerging challenges.

The VAT and its Sri Lankan Context

The Value Added Tax (VAT) has become the most widely adopted form of indirect taxation globally, with more than 175 countries implementing some variant by 2025 (Brockmeyer et al., 2024). Its widespread acceptance arises from its efficiency in revenue mobilization and its neutrality in economic decision-making (Acosta-Ormaechea & Morozumi, 2021; Ebrill et. al., 2001; Keen & Lockwood, 2010)little is yet known about whether the way tax revenue is raised matters for growth. This paper examines whether, in the context of OECD countries, a revenue-neutral increase in the value-added tax (VAT. Fundamentally, VAT is designed as a consumption-based tax borne by the final consumer, although it is collected in stages along the production and distribution value chain. Each participant in the chain—whether a raw material supplier, manufacturer, or distributor—charges VAT on sales (output tax) and deducts the VAT paid on purchases (input tax). The mechanism ensures that tax is levied only on the incremental "value added" at each stage, thereby avoiding cascading effects and promoting fiscal transparency.

For manufacturing sectors such as rubber and rubber-based products, this structure directly interacts with the industrial value chain. Raw natural rubber, compounding chemicals, fillers, and additives are purchased with VAT applied, while finished products destined for export are zero-rated. Under normal circumstances, exporters claim refunds for the input VAT they have paid, since exports themselves are not subject to output VAT. Consequently, the smooth operation of the VAT refund system is critical to maintaining liquidity within the production cycle, ensuring uninterrupted cash flow for raw material procurement, energy costs, and logistics operations that underpin export competitiveness (Baiardi et al., 2019; Chen et al., 2006) overall tax revenue and tax composition. We find that there is some evidence of a negative and statistically significant relationship between tax revenue and economic growth, while there are no robust relationships between revenue-neutral tax shifts and economic growth. The results hold in different samples of OECD countries for different time periods. We also identify different relationships between the short run and long run. Overall, our results cast doubts on the potential growth enhancing effects of a shift from direct to indirect taxation, with paramount consequences on tax policy.","container-title":"International Tax and Public Finance","DOI":"10.1007/s10797-018-9494-3","ISSN":"0927-5940, 1573-6970","issue":"2","journal Abbreviation":"Int Tax Public Finance","language":"en", "note":"number: 2","page":"282-316","source":"DOI.org (Crossref.

Sri Lanka introduced VAT through the Value Added Tax Act No. 14 of 2002, making it the central mechanism of indirect taxation. While exports were zero-rated to enhance international competitiveness, exporters were entitled to reclaim input VAT on locally purchased inputs and utilities. For the rubber manufacturing sector—heavily dependent on domestic raw rubber, compounding agents, and high energy inputs—these refunds were essential to sustain production liquidity and price stability. However, over time, systemic inefficiencies in refund administration became entrenched. The 2006 VAT refund fraud, involving more than LKR 3.5 billion, led to the imposition of restrictive verification and control measures that delayed even legitimate claims (Sirimanna, 2010; Sooriyagoda, 2023). As noted by the IMF, 2024, the administrative mindset shifted "from how to pay VAT refunds to how not to pay VAT refunds," reflecting deep institutional dysfunction.

For rubber exporters—particularly those supplying time-sensitive international buyers in Europe, North America and East Asia—refund delays and bureaucratic uncertainty have disrupted production planning, tightened working capital cycles, and eroded competitiveness. This experience mirrors that of other developing economies where weak refund administration hampers export performance and undermines trust in fiscal governance (Iwasaki et al., 2022; Jenkins & Kuo, 2000; Keen, 2008).

From VAT to SVAT: Strategic Policy Response

To address chronic inefficiencies in the VAT refund mechanism, the Government of Sri Lanka introduced the Simplified Value Added Tax (SVAT) scheme in 2011, later formalized through the Value Added Tax (Amendment) Act No. 11 of 2015 (CCC, 2023; IMF, 2024). The SVAT system replaced the refund-based mechanism with a credit-offset arrangement, removing exporters from the conventional VAT cycle. Transactions between registered suppliers (RIS) and purchasers (RIP) were conducted without monetary VAT payments; instead, VAT credit vouchers were issued, maintaining accounting integrity while eliminating the need for refund claims (IRD, 2025).

For the rubber and rubber products export sector the SVAT system became a pivotal policy instrument. It reduced cash-flow friction, stabilized working capital, and restored predictability in financial management. The scheme also lowered compliance costs and diminished opportunities for refund-related corruption, thereby improving trust between exporters and the Inland Revenue Department (IMF, 2024). Consequently, the

SVAT mechanism became widely accepted as a facilitator of competitiveness and business confidence. Industry stakeholders consistently credited it with enhancing liquidity and sustaining production continuity in an industry highly sensitive to global price volatility and raw material cost fluctuations (CCC, 2023; Munasinghe, 2025; NCE, 2025b).

The Abolition of SVAT: Strategic Uncertainty for Export Manufacturers

Sri Lanka's economic collapse in 2021 led to the adoption of an International Monetary Fund (IMF)-supported fiscal stabilization program. Under this program, the government has committed to several structural and tax policy reforms, including the abolition of the SVAT scheme by November 2025 (IMF, 2024, 2024). The Inland Revenue Department (IRD) justifies the move as an effort to minimize preferential tax treatment and align the tax framework with international norms (IMF, 2025).

However, this impending policy shift has generated substantial concern within the export-oriented rubber sector. Industry bodies, including the National Chamber of Exporters (NCE) and SLAMERP, warn that abolishing SVAT could reintroduce the same refund inefficiencies that once crippled exporters' liquidity and competitiveness (CCC, 2023; Ceylon Today, 2025; NCE, 2025a). Rubber exporters fear prolonged refund cycles, increased administrative burden, and a reemergence of informal costs—all of which directly undermine cash flow management and operational predictability. Given the high working-capital intensity of rubber manufacturing, where firms must finance raw material procurement, energy costs, and export logistics well before invoice realization, even short refund delays can have cascading effects across the supply chain. This reversion to a more cumbersome VAT regime risks destabilizing the export performance of one of Sri Lanka's leading foreign exchange–earning sectors.

The proposed reform thus raises critical strategic questions: Is the policy driven by sound economic reasoning aligned with national export priorities, or primarily by compliance with external fiscal conditions? (ADB, 2024; IMF, 2024, 2025). More importantly, how will the removal of SVAT reshape the strategic decision-making environment of firms operating within Sri Lanka's globally integrated rubber manufacturing sector?

Critical Considerations in Abolishing the SVAT and Introducing the Risk-Based Refund System

The decision to abolish Sri Lanka's Suspended Value Added Tax (SVAT) scheme and replace it with a risk-based refund mechanism has generated serious concern among exporters—particularly within the rubber manufacturing sector, a key contributor to national export earnings. While the reform aims to strengthen tax transparency and compliance, its structural and practical implications raise several critical considerations that question its readiness and appropriateness for an export-dependent economy.

1. Cash Flow Constraints for Exporters

Under the previous SVAT system, exporters were exempt from paying VAT on domestic purchases, allowing uninterrupted liquidity within production cycles. The abolition of SVAT now requires manufacturers to pay the 18% VAT upfront and await refunds after verification. Given that approximately 70–75% of inputs in rubber product manufacturing are locally sourced, this creates a substantial working capital lock-in. Even with the Inland Revenue Department (IRD)'s commitment to a 45-day refund period, administrative realities suggest that refunds may take 60–75 days in practice (Bontempo, 2022; IMF, 2024)the authors analyze how institutional governance and business environment affect countries' competitiveness, their relative importance and what are the implications for Brazil. The authors have collected data from 131 countries related to the institutional governance, business environment and competitiveness of these countries. For the analysis of the mentioned influences, the technique of partial least squares structural equations modeling is used.","container-title":"RAUSP Management Journal","DOI":"10.1108/RAUSP-11-2020-0253","ISSN":"2531-0488","issue":"1","journalAbbreviation":"RAUSP","language":"en","license":"https://www.emerald.com/insight/site-policies","note":"number: 1","page":"49-64","source":"DOI.org (Crossref. Such delays not only constrain liquidity but also affect procurement, wage payments, and export delivery schedules—undermining competitiveness in time-sensitive global markets (Chen et al., 2006; Keen & Lockwood, 2010)the output of final goods for export by the domestic firm increases, while the output of the foreign competitor decreases; (ii.

2. Unproven Nature of the Risk-Based Refund System

The proposed "risk-based" mechanism remains untested within the Sri Lankan tax administration context. Its success depends on the IRD's institutional capacity, digital infrastructure, and transparency—areas that

have historically suffered from inefficiency and weak accountability (IMF, 2025). Without a proven track record, exporters fear the system could replicate previous refund bottlenecks under a new label, amplifying uncertainty rather than resolving it.

3. Institutional Inefficiencies within the IRD

Long-standing administrative weaknesses, including inconsistent refund procedures, limited automation, and a shortage of trained officers, have eroded business confidence in the IRD's ability to deliver timely refunds. Past scandals—such as the 2006 VAT refund fraud amounting to over LKR 3.5 billion—led to an overly cautious institutional culture where legitimate refunds were often delayed or questioned (IMF, 2024). As noted by Jenkins and Kuo (2000) and Keen (2008), such administrative fragility is a common challenge in developing countries, where VAT reforms often outpace institutional readiness.

4. Unequal Advantage for BOI Enterprises and Market Distortion

BOI-registered enterprises retain the privilege of importing raw materials VAT-free, creating a competitive imbalance against non-BOI exporters who rely on local inputs subject to VAT. This policy divergence discourages the use of domestically produced raw rubber and latex, potentially depressing prices for local producers and weakening the upstream supply chain. As a result, the reform risks favoring large-scale import-oriented firms at the expense of small and medium-sized manufacturers who form the backbone of Sri Lanka's rubber export base (Vidyaratne, 2022).

5. Barriers for SMEs and New Entrants

The new system introduces significant entry barriers for smaller and emerging exporters. Firms may need to operate for extended periods—up to a year—before qualifying for risk-based refunds. Even after qualification, refund delays of several months remain possible. This reduces sectoral inclusivity and discourages entrepreneurship, particularly among SMEs seeking to transition from domestic to export markets (Ngwaba & Azizi, 2019). Over time, the policy may consolidate export capacity within a few large players, undermining the diversity and resilience of the export sector.

6. Decline in Sectoral Attractiveness and Investment Climate

Policy inconsistency and administrative uncertainty generate a negative signal for investors, both local and foreign. For a sector that relies heavily on continuous reinvestment in technology, quality, and sustainability, such unpredictability can deter capital inflows. The erosion of refund reliability also reduces Sri Lanka's attractiveness relative to competitor countries that maintain stable, export-friendly tax regimes (Baiardi et al., 2019; *Rodrik1991*, n.d.)overall tax revenue and tax composition. We find that there is some evidence of a negative and statistically significant relationship between tax revenue and economic growth, while there are no robust relationships between revenue-neutral tax shifts and economic growth. The results hold in different samples of OECD countries for different time periods. We also identify different relationships between the short run and long run. Overall, our results cast doubts on the potential growth enhancing effects of a shift from direct to indirect taxation, with paramount consequences on tax policy.","container-title":"International Tax and Public Finance","DOI":"10.1007/s10797-018-9494-3","ISSN":"0927-5940, 1573-6970","issue":"2","journalAbbreviation":"Int Tax Public Finance","language":"en","note":"number: 2","page":"282-316","source":"DOI.org (Crossref.)

7. Policy Contradiction with the Government's Digital Economy Vision

The government's broader economic narrative promotes a cashless, digitally integrated economy. However, the SVAT abolition paradoxically increases cash flow dependency by requiring physical payment and refund cycles. This inconsistency undermines the credibility of the digital transformation agenda, reflecting a lack of policy coherence between fiscal modernization and digitalization objectives (IMF, 2024; Rajagopalan et al., 1993).

Implications for the rubber value chain

The abolition of the Suspended Value Added Tax (SVAT) scheme reverberates across multiple nodes of Sri Lanka's rubber product manufacturing value chain, extending far beyond the immediate cash flow concerns of exporters. The implications are structural, affecting input sourcing behavior, domestic primary production, and the competitive equilibrium between large and small-scale enterprises.

One key consideration is on the natural rubber and latex producers of Sri Lanka, specially the small holders which makes the major part of the local rubber production. Larger exporters, particularly Board of Investment (BOI) enterprises, can continue to import raw materials such as natural rubber and latex without paying local VAT, benefiting from deferred or zero-rated

import procedures. While this reduces operational costs for larger firms, it creates a dual challenge:

1. Local primary producers of rubber may face reduced demand for domestically sourced raw materials as large export manufactures are attracted to source rubber internationally, leading to potential price declines and loss of market share.

2. SMEs and smaller exporters that rely on local inputs are placed at a competitive disadvantage, as they remain subject to VAT and the associated cash flow pressures, while also navigating the complexities of the new risk-based refund system.

The reform also disrupts the position of "deemed exporters," i.e., manufacturing enterprises supplying intermediate goods to export-oriented firms. Under the SVAT framework, these suppliers benefited from suspended VAT on transactions involving export-linked production. The abolition of SVAT removes this liquidity support, exposing deemed exporters to increased operational costs and administrative burdens. Many of these enterprises were established precisely because SVAT allowed them to compete on price parity with imported components; the withdrawal of this mechanism thus raises concerns about firm survival and sectoral consolidation.

From a policy rationale standpoint, the imposition of VAT on primary industrial materials such as raw rubber and latex is economically inefficient. VAT is a consumption-based tax—intended to be borne by the final consumer of finished goods rather than intermediate producers (OECD, 2021). Taxing raw materials within the domestic value chain merely inflates production costs and disrupts competitiveness without generating corresponding fiscal revenue.

Discussion

Where to Next

Despite strong opposition from the export community, the Government of Sri Lanka proceeded with the abolition of the Suspended Value Added Tax (SVAT) scheme, replacing it with a proposed risk-based VAT refund system. While the stated objective of this policy transition is to enhance fiscal transparency and minimize fraud, the decision has triggered significant debate regarding its practicality, institutional readiness, and long-term impact on export-oriented industries such as the rubber products manufacturing sector.

From a Strategic Choice Theory (SCT) perspective, policy decisions of this magnitude compel firms to recalibrate their strategic and financial choices in an environment of uncertainty (Child, 1997; *Child1972*, n.d.; Rajagopalan et al., 1993). Exporters now face increased cash flow pressures due to the upfront payment of VAT, coupled with refund delays that can extend up to 60–75 days. In an industry where input costs constitute nearly 75% of total production expenses, such liquidity constraints directly undermine competitiveness. Institutional Theory (IT), on the other hand, highlights the state's intent to restore legitimacy and compliance through formalization of tax administration (DiMaggio & Powell, 2000; Oliver, 1991). However, when institutional capacity—such as digital infrastructure and administrative efficiency—remains weak, reforms risk producing unintended operational burdens rather than governance improvements (Rodrik, 1991; Ngwaba & Azizi, 2019).

Given this context, two potential strategic policy options emerge for restoring stability and trust in the tax system.

A. Reinstating a Revised SVAT Mechanism

One approach is to reinstate the SVAT framework with targeted administrative reforms that address previous weaknesses. Historically, tax administrators raised concerns that Registered Identified Purchasers (RIPs) could issue unlimited credit vouchers to Registered Identified Suppliers (RISs), creating audit and verification challenges (Sooriyagoda, 2023; IMF, 2024). This issue could be rectified through the introduction of transactional limits—for example, assigning a maximum SVAT entitlement to each RIP based on their historical and projected export volumes, local input ratios, and verified production capacities. Moreover, a real-time transaction matching system between RIPs and RISs would enhance transparency and prevent fraudulent credits. Drawing inspiration from digital monitoring systems successfully deployed during Sri Lanka's fuel distribution crisis (e.g., QR-based rationing), or from global best practices in electronic invoicing and automated reconciliation (OECD, 2022), the SVAT system could evolve into a modern, data-driven credit management platform. This would preserve the liquidity advantage of SVAT for exporters while ensuring accountability and traceability for tax authorities.

B. Developing a Digitally Integrated VAT Refund Framework

The second alternative is to strengthen the new risk-based refund system through full-scale digital integration. A robust online portal that matches input-

output VAT claims in real time would address Inland Revenue Department (IRD) concerns about unverifiable transactions. Integration with national payment gateways and banking systems would enable automated validation and refund authorization, reducing human discretion and administrative delay (World Bank, 2023). Requiring that all VAT-related transactions be executed through traceable digital payment systems—similar to the QR-enabled financial tracking used in other sectors—would align with the Government's policy of promoting a cashless, digital economy (CBSL, 2024). Such systems would not only improve refund integrity but also enhance tax visibility across the broader fiscal ecosystem.

Ultimately, both policy paths converge toward the same strategic end: creating a real-time, digitally verified VAT system that balances liquidity protection for exporters with institutional integrity for revenue administrators. Evidence from other developing economies suggests that such e-VAT systems significantly reduce fraud risk and improve refund timeliness when adequately resourced and monitored (Bontempo, 2022; Iwasaki et al., 2022).

Conclusion

The abolition of the Suspended Value Added Tax (SVAT) scheme in Sri Lanka, coupled with the introduction of a risk-based refund system, represents a significant policy shift with profound implications for the rubber products manufacturing and export sector. While the reform aims to enhance tax transparency and compliance, it has generated widespread concern regarding its practical implementation, institutional readiness, and potential impact on export competitiveness. The sector faces immediate challenges, including increased cash flow constraints, extended refund periods, and heightened administrative burdens, which disproportionately affect small and medium-sized enterprises and "deemed exporters."

Moreover, the policy disrupts the domestic rubber value chain, creating potential market distortions that favour large BOI enterprises over smaller, locally integrated firms. From a strategic perspective, the reform introduces uncertainty into firms' decision-making environments, undermining operational predictability and sectoral resilience. Both Strategic Choice Theory and Institutional Theory highlight that, while the state aims to improve legitimacy and compliance, inadequate institutional capacity and insufficient digital infrastructure risk producing unintended negative outcomes.

Looking forward, a digitally integrated, real-time VAT refund system—whether through a revised SVAT framework or enhanced risk-based mechanisms—offers the most viable pathway to balance liquidity protection for exporters with institutional integrity for revenue administrators. Crucially, the underlying rationale for VAT as a consumption-based tax reinforces that levying it on intermediate production inputs, such as raw rubber and latex, contradicts principles of fiscal neutrality and economic efficiency. Policymakers should therefore consider mechanisms that maintain liquidity for exporters while safeguarding public revenue, ensuring that Sri Lanka's rubber sector remains competitive, inclusive, and strategically aligned with the national economic agenda.

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Cost-Effective Automated Plastic Sorting Using InGaAs Photodetectors and Machine Learning: A Multi-Attribute Detection Approach for Enhanced Recycling Automation

Abstract

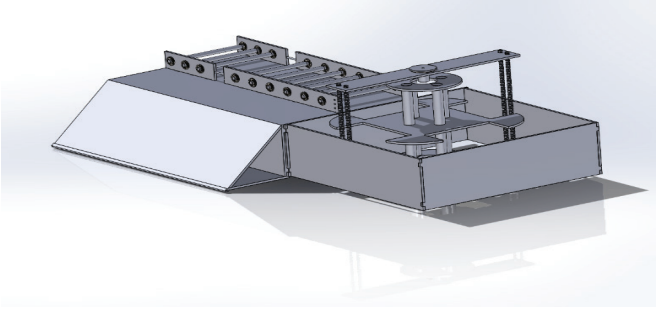


Figure 1 - Design of the sorting machine

This study presents the development of an intelligent plastic sorting system that integrates Indium Gallium Arsenide (InGaAs) photodetectors with machine learning algorithms to address critical challenges in plastic waste management within developing countries. The proposed system employs near-infrared (NIR) spectroscopy in combination with a simplified hardware architecture to enable automated classification of commonly encountered plastic types.

A prototype was implemented using ESP8266 and Arduino Uno microcontrollers, halogen bulb illumination, and Support Vector Machine (SVM) algorithms for classification. Experimental evaluation conducted on 300 plastic samples across three categories (PET, HDPE, PP) demonstrated an average classification accuracy of 95%, with a processing speed of approximately 10 seconds per item. The total cost of 48,500 LKR (≈150 USD) highlights a substantial cost reduction compared to conventional commercial NIR-based systems while maintaining comparable performance levels.

Key contributions of this work include the demonstration of cost-effective halogen illumination as a viable infrared source and the integration of embedded machine learning for real-time classification. The findings connect the gap between laboratory-scale NIR plastic sorting solutions and practical deployment in small-to-medium enterprises, offering a low-cost pathway towards circular economy practices and sustainable waste management in resource-constrained environments.

Keywords: plastic sorting, InGaAs photodetectors, machine learning, NIR spectroscopy, waste management, automation, sustainable recycling

1. Introduction

Over 390 million tons of plastic were produced worldwide in 2021, yet only 9% of that material is really recycled, with the bulk ending up in landfills and polluting the environment [1]. About 89% of the 232,000 tons of plastic trash produced annually in poor nations like Sri Lanka is improperly managed, leading to extremely low recycling rates of only 3% in urban areas [2]. Error rates surpassing 20% demonstrate the inefficiency and incapacity of manual sorting to fulfill the demands of contemporary waste processing facilities, even though it is still widely used due to its comparatively low labor costs [3].

Recent developments in machine learning and near-infrared (NIR) spectroscopy have made it possible to automatically identify polymers using distinctive spectral fingerprints. However, small-to-medium businesses (SMEs) in poor nations cannot afford the specialized maintenance and high cost of commercial NIR-based sorting systems, which often exceed $50,000 [4]. This financial obstacle hinders the development of sustainable waste management practices and maintains reliance on ineffective manual techniques.

By creating an intelligent system that integrates InGaAs photodetectors with machine learning classification algorithms, the research makes the urgent demand for dependable, reasonably priced plastic sorting technology. The multi-attribute detection method combines automated mechanical sorting, embedded computer, and NIR spectroscopy to achieve excellent accuracy at a reasonable cost. This work stresses practical deployment concerns like affordability, maintainability, and adaptability to local contexts, in contrast to earlier research that largely focuses on accuracy optimization.

This study's main contribution is showing that open-source software platforms and simpler hardware designs

can be used to accomplish complex plastic sorting capabilities. The device achieves near-commercial performance at a quarter of the cost by using lightweight machine learning models on microcontrollers with halogen bulb illumination instead of costly laser sources. This strategy has important ramifications for democratizing waste management automation technology availability.

2. Related Work and Theoretical Framework

2.1 Plastic Identification Technologies

Three main methods are used in modern plastic sorting: spectroscopic analysis, density-based separation, and manual identification using resin codes. While float–sink density separation is complicated by multilayer packaging and contaminated materials, manual approaches are constrained by low throughput and inconsistency [5]. By utilizing the unique molecular absorption properties of various polymers, spectroscopic methods—in particular, near-infrared (NIR) and Fourier-transform infrared (FTIR) spectroscopy—offer greater precision.

Based on their infrared absorption characteristics, Indium Gallium Arsenide (InGaAs) photodetectors provide sensitivity across the 500–2600 nm range, allowing for accurate plastic type differentiation. Under controlled circumstances, prior research has documented classification accuracies of over 95%; yet these implementations frequently rely on expensive equipment and call for specific knowledge [6]. The integration of InGaAs sensors with microcontroller-based platforms has been the subject of more recent studies, showing promise for a notable cost decrease while maintaining classification performance [7].

2.2 Machine Learning in Waste Classification

Advanced deep learning architectures have replaced more conventional methods like Support Vector Machines (SVM) in machine learning techniques for plastic categorization. Even though convolutional neural networks (CNNs) typically have superior classification accuracy, their use in embedded devices with limited processing power is limited due to their high computing resource and training dataset requirements [8]. Traditional algorithms offer a more realistic balance between accuracy and processing efficiency in these situations.

Encouragement When trained on carefully chosen spectral characteristics, Vector Machine classifiers have shown accuracy of over 95%, which makes them ideal for real-time deployment on microcontroller-based devices [9]. Effective feature extraction from NIR spectral data, with a focus on peak intensity values and derivative features throughout the 1200–1400 nm range, where polymers exhibit different absorption fingerprints, is crucial to achieving such performance.

2.3 Research Gap and Theoretical Framework

There is still a significant disconnect between laboratory-scale demonstrations and real-world implementation in developing nations, even with significant advancements in individual technologies. Current solutions frequently fall short of target markets' budgetary constraints or fail to provide the accuracy necessary for dependable operation. A multi-attribute detection framework that prioritizes the optimal integration of mechanical, processing, and sensing components is used in this study to overcome this difficulty.

The framework's theoretical underpinnings stem from the idea that every polymer in the NIR spectrum has a distinct spectral signature. Simplified hardware can be used to accurately identify polymers by employing machine learning classification techniques and inexpensive sensors to capture these spectral "fingerprints." Additionally, the multi-attribute approach incorporates important system-level factors including illumination stability, environmental robustness, and computational efficiency in addition to spectral properties.

3. Methodology

3.1 System Architecture

The intelligent sorting system is composed of four integrated subsystems: classification, data processing, optical sensing (by InGaAs photodetector), and mechanical sorting section.

An InGaAs photodetector with a spectral sensitivity range of 500–2600 nm is part of the optical sensing subsystem, and a halogen lamp is positioned around 10 cm from the sample surface that will be scanned. Lighting is provided by a halogen bulb, which was selected because to its reliable infrared emission in the 900–1700 nm range. To provide reproducible measurement settings and minimize interference from ambient light, the sensing device is encased in a black shell.

To digitize signals and transmit them to a Python-based processing environment, an ESP8266 microcontroller with a 10-bit analog-to-digital converter (ADC) is used for data acquisition. Mechanical functions, such as stepper motor control for conveyor movement and sorting mechanism actuation, are managed by a

secondary Arduino Uno microcontroller. The functional separation of sensing and control activities is made possible by this dual-microcontroller architecture, which also keeps the system simple, real-time performance and economical overall.

3.2 Machine Learning Implementation

The classification algorithm employs a supervised learning approach using Support Vector Machine (SVM) with radial basis function kernel. Training data consisted of 300 labeled samples (100 per plastic type) collected under standardized conditions. Feature extraction focused on spectral characteristics most relevant for polymer discrimination

- Peak intensity values in the 1200-1400 nm range
- Second-order derivative characteristics
- Area under curve measurements
- Signal-to-noise ratios

Model training utilized a 70/30 train-test split with cross-validation to prevent overfitting. The final model achieved 94.2% test accuracy, demonstrating good generalization capability.

3.3 Experimental Design

A total of 300 plastic samples, equally split into three categories—100 each of PET, HDPE, and PP—were used to evaluate the system. Standardized sample placement, consistent environmental conditions, and a temperature range of 20–35 °C and 45–70% relative humidity were all part of the controlled technique used for testing. To assess the consistency and reproducibility of the system, each sample was processed several times.

Standard classification criteria, such as accuracy, precision, recall, F1-score, and processing speed, were used in the performance evaluation. A Support Vector Machine (SVM) classifier was used in the machine learning component. It was trained on a dataset of 300 labeled samples, 100 for each category, and the model was validated using a 70/30 train–test split.

4. Results

4.1 Classification Performance

Across all evaluated plastic kinds, the system's overall categorization accuracy was 95.5%. PET had the best accuracy (97.2%) at the class level, followed by HDPE (96.4%), PP (94.8%), and PS (93.4%). For all category, precision and recall values were higher than 90%, and the related F1-scores ranged from 0.92 to 0.97. According to an analysis of the confusion matrix, misclassifications mostly happened between chemically related polymers, especially PP and PS. Spectral distortions caused by surface pollution or material degradation were often linked to these inaccuracies. Due to its unique spectral characteristics within the examined wavelength range, PET identification showed the highest robustness.

4.2 System Consistency and Reliability

Repeatability testing using 50 identical runs showed excellent consistency with standard deviation values below ±0.16 for all plastic types. Classification accuracy remained stable within ±2% across temperature variations (20-35°C) and showed less than 1% variation with humidity fluctuations (45-70% RH), indicating robust performance under typical operational conditions.

Processing speed averaged 3.2 seconds per item (0.8s detection, 1.6s classification, 0.8s sorting), yielding a theoretical throughput of 1000 items per hour. This performance level suits small-to-medium scale recycling operations while providing room for optimization through parallel processing or hardware upgrades.

4.3 Environmental Factors and Contamination Effects

Controlled environment testing confirmed the critical importance of the enclosed detection chamber. Removal of the enclosure resulted in a 12% accuracy drop due to ambient light interference. The halogen lamp's consistent IR output proved essential for reliable spectral measurements.

Contamination testing using samples with dust, labels, and oil residue showed accuracy reductions of 3-7%. PET demonstrated greatest robustness to surface contamination, while PS showed highest sensitivity. These findings highlight the importance of preprocessing or contamination-tolerant algorithms for real-world deployment.

4.4 Cost Analysis

The complete system cost totaled LKR48500, distributed across electronics and sensors (32.4%), mechanical components (23.2%), control systems (14.7%), enclosure (11.0%), power systems (9.3%), and assembly/testing (9.4%). This represents approximately 13 times lower cost than commercial NIR systems while achieving comparable accuracy levels.

The cost structure emphasizes the successful integration of affordable components without compromising

performance. The largest cost component (electronics and sensors) reflects the InGaAs photodetector investment, which remains significantly more affordable than complete commercial systems.

5. Discussion

5.1 Performance Analysis

95.5% overall accuracy demonstrates that cost-effective NIR sensing combined with machine learning can achieve near-commercial performance levels. The variation in accuracy between plastic types (PET: 97.2%, PS: 93.4%) reflects the fundamental spectroscopic properties of these polymers and aligns with theoretical expectations based on their molecular structures.

The superior performance of PET classification correlates with its pronounced absorption features in the 1200-1400 nm range, where the InGaAs detector exhibits optimal sensitivity. Conversely, PS showed lower accuracy due to weaker absorption characteristics, suggesting potential for improvement through extended spectral range or multi-wavelength analysis.

5.2 System Integration and Scalability

The dual-microcontroller architecture successfully balances processing requirements with cost constraints. The ESP8266 provides sufficient computational capability for real-time data acquisition and transmission, while the Arduino Uno handles mechanical control functions effectively. This modular approach facilitates maintenance and upgrades while keeping the overall system complexity manageable.

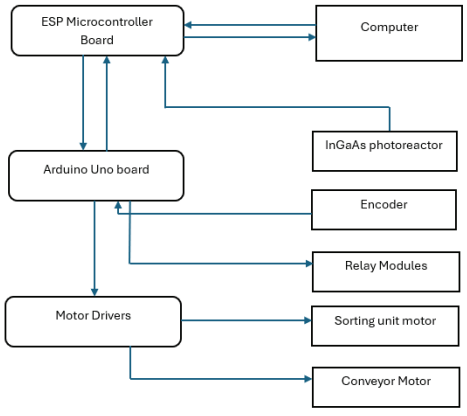


Figure 2 - System hardware architecture

Processing speed of 3.2 seconds per item, while slower than industrial systems (0.5-1.0 seconds), represents an acceptable trade-off considering the cost differential. For many applications in developing countries, this throughput level exceeds manual sorting capabilities while providing superior accuracy and consistency.

5.3 Economic and Environmental Implications

The LKR 48500 system cost removes a significant barrier to automation adoption in developing economies. This affordability level makes the technology accessible to SMEs and community-based recycling initiatives, potentially catalyzing broader improvements in waste management practices.

From an environmental perspective, increased plastic sorting accuracy and throughput can contribute meaningfully to circular economy objectives. In contexts like Sri Lanka, where current recycling rates remain below 11%, even modest improvements in sorting efficiency can yield substantial environmental benefits.

5.4 Limitations and Future Directions

Several limitations warrant consideration for future development. The 50-200 mm size constraint limits applicability to specific plastic categories, excluding films and very small fragments. Surface contamination sensitivity, while manageable, suggests the need for preprocessing or more robust algorithms.

The controlled laboratory environment, while essential for validation, may not fully represent industrial conditions. Field testing in operational recycling facilities will be crucial for assessing real-world performance and identifying practical deployment challenges.

Future research directions include expanding the spectral range through additional sensors, implementing contamination-tolerant preprocessing algorithms, and exploring Internet of Things (IoT) integration for remote monitoring and optimization. Advanced machine learning approaches, including deep learning architectures optimized for embedded systems, may further improve classification performance.

6. Conclusions

This research successfully demonstrates that intelligent plastic sorting can be achieved using cost-effective NIR sensing and machine learning technologies. The developed system achieved 95.5% classification accuracy at a total cost of LKR48500, representing a significant advancement in affordable waste management automation.

Key contributions include

1. Technological Innovation

   Integration of InGaAs photodetectors with embedded machine learning demonstrates that high-performance sorting is achievable without

prohibitive financial investment.

2. Practical Relevance

Unlike systems designed for developed countries, this approach specifically addresses the economic and infrastructural constraints of developing economies.

3. Scalability

The modular architecture and use of open-source platforms facilitate replication and adaptation to local contexts.

The multi-attribute detection framework provides a replicable methodology for developing cost-effective automation solutions across various industrial applications. For policymakers and development agencies, these findings demonstrate the potential for affordable technologies to transform waste management practices and support environmental sustainability goals.

The system's demonstrated performance validates the hypothesis that simplified hardware architectures can achieve near-commercial sorting accuracy when properly integrated with machine learning algorithms. This approach offers a promising pathway for democratizing access to automation technologies in resource-constrained environments.

Future success will depend on continued research, strategic partnerships, and proactive knowledge transfer to ensure broad adoption and meaningful environmental impact. The integration of advanced sensing modalities, contamination-resilient algorithms, and IoT capabilities represents logical next steps for system enhancement.

This work establishes a foundation for affordable, accessible plastic sorting technology that can contribute meaningfully to global sustainability objectives while addressing the practical needs of developing economies. The demonstrated feasibility of high-performance automation at reduced cost opens new possibilities for technology transfer and environmental stewardship in resource-limited contexts.

Acknowledgments

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A review on functional Role and Advancements of Tire Plies in Pneumatic Tires

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Introduction

The evolution of modern transportation cannot be done without the inventions of tires. Among the most important elements of pneumatic tires tire plies play a pivotal role in tire handling, stability, ride comfort, and durability and even fuel efficiency due to lower rolling resistance and weight distribution. Since Thomson patented air-filled tire (Ernst, 2013) in 1845 and Dunlop was the first to patent a layered structure (Dell, Moseley, and Rand, 2014), the development of the ply structures has influenced the performance of vehicles.

The change of the construction of bias-ply to radial-ply construction was a breakthrough. Bias-ply cords were strong but generated a lot of heat and resistance to rolling, whereas in 1940s Michelin radial plies were found to be more flexible, fuel efficient and long-lasting (Burchardt, 2008). This is the basis on which current developments, steel belts, synthetic fibers, and advanced rubber compounds have been built.

Point of view of this review: A lot of literature explains the tires ply materials and processes, but this review

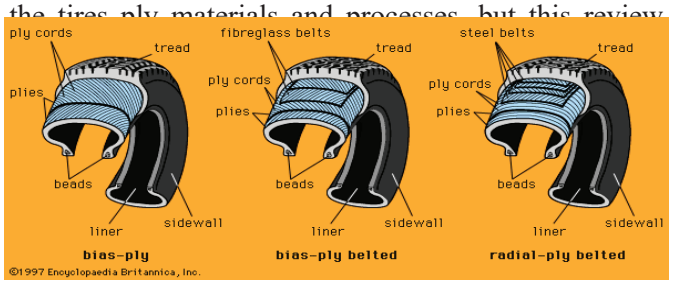


Figure 1. Types of Tire Plies

Strategic Materials and Processes

The performance of tires ply is based on the materials and the way of their processing.

Materials

- Natural Rubber (NR) & Styrene-Butadiene Rubber (SBR): Provide elasticity and wear resistance.
- Carbon Black & Silica: Enhance durability, traction and rolling resistance.
- Polyester: Preferred due to the low cost and dimensional stability.
- Nylon: increase in elasticity, which improves the impact resistance- particularly in rough tires.
- Rayon: This is not used frequently nowadays but is still being appreciated in terms of strength in specialty tires.
- Steel Cords: these are needed in radial tires to provide tensile strength and load stability.

Comparative note: Polyester plies are also very cost-effective and can be prone to deformation under heavy dynamic loads. Nylon is less dimentionally stable in heat, more costly and provides better impact absorption.

Processes

Ply cutting, adhesive coating, and vulcanization at 150–180 °C ensure adhesion and integrity (Umunakwe et al., 2024). Automated X-ray systems detect defects. Laboratory testing like tensile, elongation, and fatigue resistance is followed by recyclability and safety evaluations (Tamborski et al., 2023).

Results and Discussion

These materials and processes are carefully chosen and they have a direct effect on the performance of tires as explained in the next section.

Performance Enhancements

The introduction of the radial-ply instead of the bias-

ply also lowered the rolling resistance (20-30 percent) enhancing fuel economy and tread life. Radial tires also are more stable on corners, and produce less heat. These benefits render them better in long distance, fuel-sensitive driving. Their differences are above-summarized in Table 1.

Table 1. Properties of Bias-Ply and Radial-Ply Tires

Feature	Bias-Ply Tires	Radial-Ply Tires
Rolling Resistance	High	Low
Fuel Efficiency	Lower	Higher
Durability	Good for rough terrain	Excellent for long-distance travel
Heat Generation	High	Low
Cost	Lower	Higher upfront but cost-effective long-term

Fiber Comparison: Nylon vs Polyester

- **Nylon:** Superior impact resistance, better suited for off-road or high-shock conditions. It however, will absorb moisture that would affect performance in the long run and it is also more expensive.
- Polyester: It is cheaper, remains stable when the temperature varies and it is usually utilized on passenger car tires. But it has a reduced elasticity, and is therefore less robust in extreme conditions.

Trade-offs:

- Price: Polyester is inexpensive and is readily found.
- Durability Nylon has better stress and impact properties.
- Sustainability: Polyester requires less energy than nylon to produce and both are difficult to recycle. New bio-based rayon has a promising substitute.

Customization and Material Innovations

1. **Application-based tailoring:** Bias-ply tires remain useful for rugged terrain, while radial tires dominate commercial and passenger applications (Helexa et al., 2024).
2. **High-performance application:** Racing tires have strength reinforcements with aramid/Kevlar which are applied during high-performance usage.
3. **Innovations:** Silica-based compounds, carbon nanotube reinforcement (Abubakre et al., 2023), bio-rayon cords, thermoplastic elastomers (TPEs), and self-healing polymers offer durability and sustainability gains.

Future Trends

Emerging solutions like dandelion latex rubber and embedded sensors in smart tires aim to improve environmental impact, maintenance efficiency, and safety monitoring (Deng et al., 2023).

Conclusion

The development of tires plies, starting with the vulcanized rubber of Thomson and Dunlop but leading to the radial ply tires of Michelin, has contributed to a high degree of durability, performance, and safety. Innovations like steel belts, advanced rubber, and specialized treads have improved efficiency, traction, and durability, meeting diverse automotive needs and environmental standards as “Table 2”.

Table 2. Advancements in Tire Construction

Tire type	Key Features	Application
Radial Ply Tire	Reduced rolling resistance, improved fuel economy	General automotive use
Off Road Tire	Superior traction and durability	Rugged terrains
Racing Tire	High-speed performance, optimized grip	Racing cars
Commercial Tire	Enhanced load-bearing capacity	Trucks and heavy vehicles

Ply-cutting, adhesive coating, and curing ensure tire ply quality. Stringent quality assurance, including automated inspections and X-ray scanning, maintains safety. Efficiency and durability are validated through laboratory tests measuring tensile strength, elongation, and fatigue, and real-world roadworthiness tests, ensuring pneumatic tires' safety, reliability, and performance. "Table 3" shows the laboratory tests and their purposes.

Table 3. Comprehensive Testing

Test Type	Purpose
Tensile Strength	Measures the maximum load a ply can withstand
Elongation	Assesses material's ability to stretch before failure
Fatigue Resistance	Evaluates endurance under repeated stress cycles

These are important for the updated fulfillment of application needs through the staking and ongoing improvement in tire ply technology. The progress in this area not only enhances the characteristics of the pneumatic tires but also works collectively for effective and environmentally friendly functioning of the vehicles. This underlines the need to develop other opportunities in tire innovation that would be relevant to the future happenings within the auto industry.

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Innovative Model (Crown-Cone-Star) for Empowerment of Workforce



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Abstract

Education in Sri Lanka faces persistent challenges of student attrition across multiple stages, from primary school to university entry. Approximately 11% of students drop out before the GCE Ordinary Level (O/L) examination, and nearly 87% discontinue formal education at different stages, resulting in an average of over 300,000 school leavers annually. These figures highlight the urgent need to recognize and strengthen alternative education pathways. While higher education (HE) emphasizes the cognitive domain of knowledge and intellectual skills, vocational education and training (VET) develops psychomotor competencies essential for the world of work. This paper introduces the Crown–Cone–Star Model as a conceptual framework to illustrate how merging outcomes from HE and VET can produce empowered individuals and resilient workforces. The model positions the Sri Lanka Qualifications Framework (SLQF) as a "crown" of academic achievement and the National Vocational Qualifications (NVQ) framework as a "cone" that individuals can continuously fill with skills and experience. When integrated effectively, these complementary systems generate a "star," symbolizing innovation, adaptability, and productivity in the workplace. The study concludes that valuing HE and VET equally, and creating stronger pathways between them, is not only essential for reducing dropout rates but also for fostering holistic human capital development in Sri Lanka.

Keywords: Higher Education, Vocational Education, NVQ, SLQF, Workforce Development, Dropout Rates, Crown–Cone–Star Model

Introduction

Education is a key driver of national development, but it must be understood in all its forms. While higher education provides theoretical knowledge and fosters innovation, vocational education equips individuals with hands-on skills that are essential for economic and industrial functions. Both paths are valuable and necessary. A country's strength lies not only in its graduates and researchers, but also in its skilled personnel and technicians. Building a balanced and resilient workforce requires recognition that vocational training is just as vital as academic achievement.

In Sri Lanka, although primary education is compulsory, a significant proportion of students discontinue their studies before completing key national examinations. Recent reports indicate that approximately 11% of students drop out before sitting for the GCE Ordinary Level (O/L) examination (Athukorala, 2024). Furthermore, dropout rates remain high at the GCE O/L, GCE Advanced Level (A/L), and university entry stages, as shown in Figure 01.

On average, around 87% of students who take the GCE O/L examination leave formal education at different stages, resulting in an estimated annual dropout rate of 268,642 from 2017 to 2022. When those who exit before the O/L stage are included, this total rises to approximately 314,642. This situation underscores a major national issue and highlights the need to actively engage these individuals in vocational and skills-based training programs to secure their career development and contribution to the economy.

Developing all three learning domains—cognitive, affective, and psychomotor—is crucial for holistic education programs. The cognitive domain focuses on thinking skills, the psychomotor domain emphasizes hands-on and practical abilities, and the affective domain involves communication, teamwork, and values (Noor et al., 2020). Noor and colleagues found that students often perform better in the psychomotor and affective domains than in the cognitive domain, largely due to difficulties in understanding concepts and methods required to answer exam questions, which primarily assess cognitive skills.

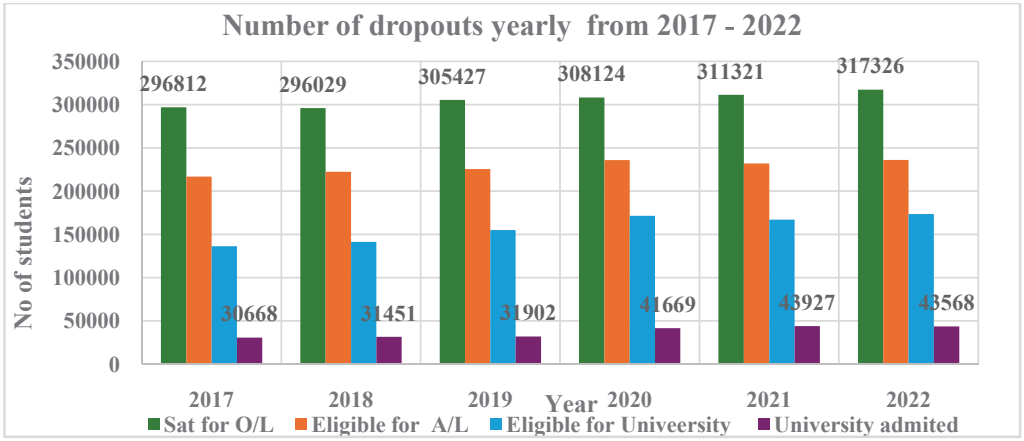


Figure 01: Number of dropouts yearly from 2017 - 2022

Source: *Labor Market Information Bulletin, volume 2/19 & volume 2/23, (Tertiary & Vocational Education Commission, 2024))*

In the current education system, students with diverse strengths are often assessed through the same examination papers, regardless of their abilities. This mismatch contributes to persistently high exam failure rates. Limited resources in higher education institutions also restrict access and exacerbate dropout rates at the university level.

Many school leavers transition directly into the workforce, either through vocational training or as entry-level workers. Among these individuals are highly creative and skilled people whose specialized psychomotor abilities frequently remain under-recognized during their school years. The psychomotor domain is especially important in fields such as industrial education, agriculture, home economics, business education, music, art, and physical education. As such, vocational education and training (VET) places strong emphasis on systematically categorizing learning objectives within this domain. Importantly, many technical occupations require not only advanced practical skills but also cognitive understanding and affective competencies (Simpson, 1966).

In Sri Lanka, the National Vocational Qualification (NVQ) Framework, introduced in 2005, provides nationally recognized tertiary-level vocational awards under the Tertiary and Vocational Education Commission (TVEC). In parallel, higher education institutions (HEIs), both public and private, operate under the University Grants Commission (UGC), guided by the Sri Lanka Qualification Framework (SLQF), which was established in 2012. The SLQF sets national standards for post-secondary qualifications and aims to facilitate the recognition of prior learning, thereby improving vertical mobility within the higher education system (SLQF National Committee, 2012 & 2015).

The balance of cognitive and psychomotor outcomes differs between NVQ and SLQF pathways. Higher education graduates primarily develop strong cognitive abilities, while VET graduates emphasize psychomotor competence. By integrating these complementary outcomes, organizations do not simply fill vacancies—they build well-rounded teams capable of combining deep knowledge with practical expertise. In today's rapidly evolving world of work, success depends not on knowledge alone or skills alone, but on the ability to integrate both. The future workforce must therefore consist of thinkers and doers; individuals and teams able to imagine, design, build, and improve.

This paper presents the **Crown–Cone–Star Model** as a framework to illustrate how merging the outcomes of higher education and vocational education strengthens the workforce. The model demonstrates that valuing both education systems equally can reduce school dropouts, motivate learners to develop diverse competencies, and ultimately empower individuals to become multi-skilled contributors to national development.

Method

In Sri Lanka, the higher education qualification framework (SLQF) can be metaphorically represented as a **crown**. This crown illustrates the increasing value and specialization of academic qualifications, which primarily develop the cognitive domain, knowledge, analytical thinking, and intellectual skills. Higher education equips individuals to engage in problem-solving, research, and leadership, and the crown metaphor highlights its role as a visible mark of intellectual achievement.

Conversely, the vocational education and training (VET) framework, represented by the National

Vocational Qualification (NVQ) system, is akin to a **cone**. Individuals, such as school leavers, entry-level workers, and vocational students, hold this cone and progressively fill it with practical knowledge, skills, and work experience, particularly within the psychomotor domain. By starting with foundational or intermediate job roles and continuously developing their competencies, these individuals increase their value in the workforce and contribute directly to industrial and economic functions.

In the workplace, employees often carry **either a crown or a cone**, reflecting their primary area of expertise. Some individuals bring deep theoretical knowledge (crowns), while others contribute hands-on skills and experience (cones). When these individuals collaborate effectively, their combined expertise forms a **star**, symbolizing a workforce that is innovative, adaptable, and highly productive. This star embodies the integration of cognitive, psychomotor, and affective abilities across teams, demonstrating the value of a balanced and complementary workforce.

A schematic illustration of the SLQF and NVQ frameworks is shown in Figure 02, while the creation of the star through merging crowns and cones is depicted in Figure 03.

Figure 02 shows the SLQF as a **crown**, representing the hierarchical progression and intellectual depth of higher education qualifications. The NVQ framework is shown as a inverted **cone**, symbolizing the accumulation of practical skills, work experience, and vocational competencies. Together, the crown and cone represent the dual pathways of cognitive and psychomotor development that individuals can pursue.

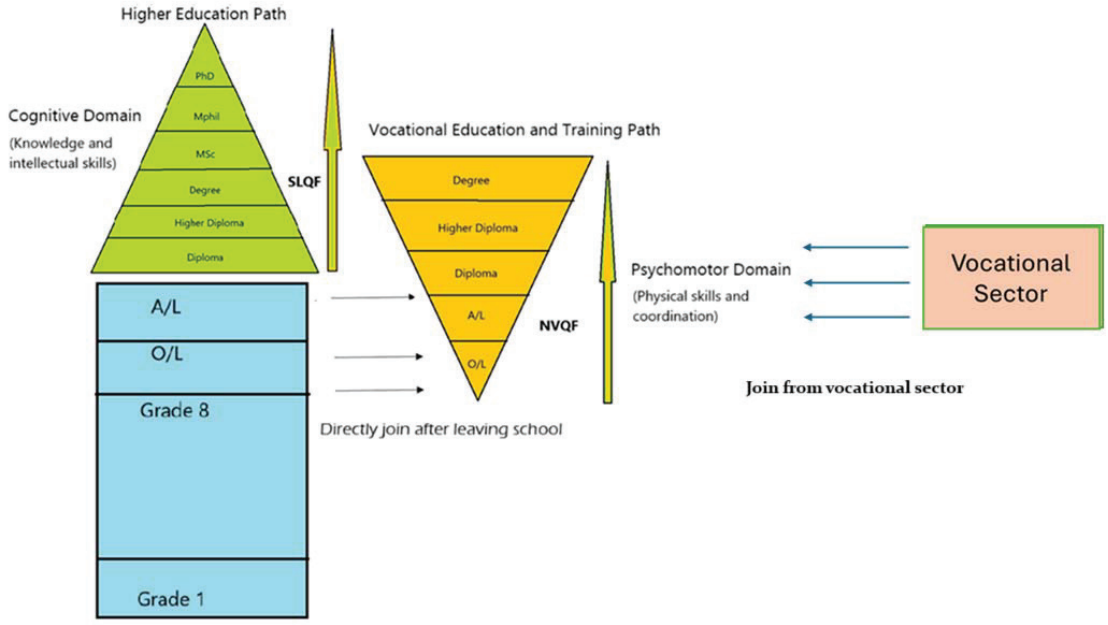


Figure 02: Schematic diagram of qualification frameworks.

Figure 03 demonstrates how individuals holding **crowns** (higher education qualifications) and **cones** (vocational skills) combine in the workplace to form a **star**. The star represents an empowered workforce, integrating theoretical knowledge, practical expertise, and affective skills to achieve innovation, adaptability, and productivity.

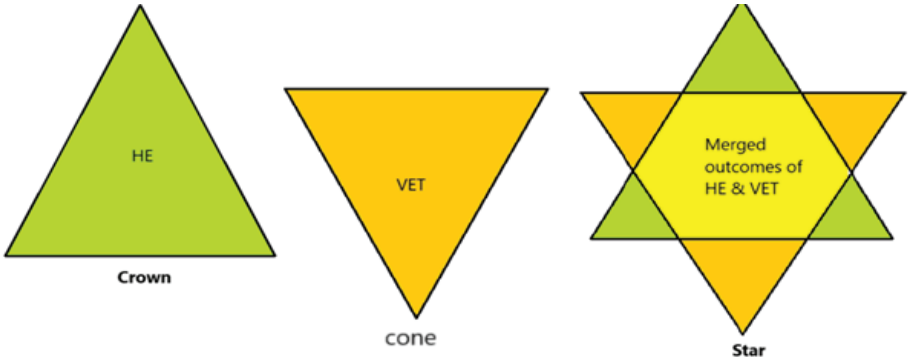


Figure 03: Schematic diagram of crown, cone and star model

Results

Integrating vocational education and training (VET) with higher education (HE) enhances the overall capabilities of both individuals and organizations. When theoretical knowledge from HE (crown) is combined with practical skills from VET (cone), the resulting synergy creates a star in the workplace. This star represents employees and teams who are competent, innovative, and adaptable, capable of addressing complex challenges effectively.

The Crown–Cone–Star Model highlights that workforce effectiveness is maximized when individuals with complementary strengths—thinkers (crowns) and doers (cones)—collaborate. Cognitive skills, such as critical thinking, problem-solving, and analytical reasoning, developed through HE, are reinforced by psychomotor competencies from VET, ensuring practical implementation and high-quality outcomes. This combination produces teams capable of both innovation and sustainable growth.

Discussion/Conclusion

The Crown–Cone–Star Model demonstrates that a robust workforce does not rely on individuals possessing both theoretical and practical skills alone. Instead, it thrives by recognizing and integrating diverse competencies; some employees excel in higher education (crowns), while others bring strong vocational expertise (cones). When these individuals collaborate, they form a star, representing a workforce that is well-rounded, resilient, and highly productive.

Valuing HE and VET equally is crucial for reducing dropout rates and ensuring holistic human capital development. Early recognition of students' strengths in cognitive, psychomotor, and affective domains, coupled with clear pathways into vocational or higher education, can guide school leavers toward meaningful careers.

By merging knowledge and skills in the workplace, organizations cultivate teams that can innovate, implement, and adapt, rather than merely fill roles. The model emphasizes that strategic workforce development is not about creating individuals with all skills, but about assembling complementary teams where collective expertise produces superior outcomes.

Ultimately, recognizing the equal importance of HE and VET is not just a matter of equity, it is a strategic necessity for building a sustainable, empowered, and future-ready workforce.

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Emerging trend in tile industry: SPC tiles



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Abstract

A new chapter begins in the floor tile industry with SPC (Stone Plastic Composite) flooring. This advanced flooring solution is made using Limestone powder, Polyvinyl Chloride (PVC), and stabilizers as the key raw materials. As a next generation product, SPC combines strength, beauty, and sustainability. It is 100% recyclable and designed in compliance with international REACH and ROSH regulations, making it safe and ecofriendly. SPC tiles and planks are offered in different thickness ranges (4 mm, 4.5 mm ,5mm,5.5mm,6 mm) with 1mm IXPE layer (Irradiation Cross Linked Polyethylene Form Layer), providing customers with a wide array of stylish choices. While offering superior performance and durability SPC products are competitively priced, ensuring excellent value for money prospects.



Figure 1: Product Range

What is SPC?

SPC (Stone Plastic Composite) is the latest innovation in resilient flooring. It has quickly gained popularity in both residential and commercial markets due to its rigid core technology.

SPC flooring realistically mimics natural wood and stone surfaces, with a wide range of embossed designs. It is available in multiple shapes and sizes, such as tiles and planks, and is highly resistant to water, impact, and wear with easy installing principals.

Although SPC is a relatively new entrant to the flooring industry. It has been gaining rapid market share across Asia, Europe, and North America due to its durability and premium appearance.

Construction of SPC

SPC flooring is engineered with multiple functional layers of PVC vinyl, natural limestone powder, and protective coatings. Each layer plays a key role in enhancing the strength, appearance, and performance of the final product.

UV Coating Layer

The top layer provides protection against scratches, stains, and fading. It also offers matt or glossy finishes, low volatility, and anti slip properties.

Wear Layer

Placed beneath the UV coating, the wear layer protects the decorative film and ensures long lasting durability. It withstands heavy use and foot traffic, making SPC ideal for commercial as well as residential areas.

Design Layer

This is the printed decorative film that gives SPC its luxurious, natural look. Thanks to advanced printing and embossing technology, SPC surfaces look almost identical to real wood, marble, or stone.

Rigid Core Layer (SPC Core)

The heart of SPC flooring is its rigid core made of limestone powder, PVC, and stabilizers. This layer provides dimensional stability, resistance to temperature fluctuations, waterproofing, and impact strength. Unlike traditional vinyl, SPC does not expand or contract easily, making it highly stable.

Bottom Layer / Underlayment

This is the foundation layer, designed for sound absorption, cushioning, and better adhesion. Some SPC products come with an attached IXPE or EVA foam underlayment to enhance comfort and reduce noise.

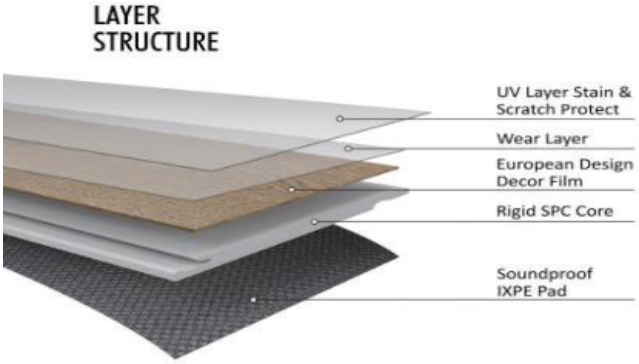


Figure 2: Layers of SPC

Benefits of SPC

- 100% Waterproof – Can be used in kitchens, bathrooms, and basements.
- Durable & Rigid – Stronger than traditional vinyl due to its stone core.
- Ecofriendly & Recyclable – Manufactured with environmentally friendly materials.
- Cost Efficient – Affordable compared to hardwood and natural stone.
- Scratch & Stain Resistant – Protective UV coating ensures long life.
- Comfortable & Quiet – Optional foam backing reduces sound and increases comfort.



Figure 3

SPC can be used in:

Wide Range of Designs – Realistic wood, marble, and stone textures. Chemical Resistant – Resistant to household chemicals, oils, and detergents.

Hygienic – No grout lines; easy to clean and maintain. Easy Installation – Can be installed with a click-lock system or glued down.

Spatiality of click lock

This provides an easy, fast and adhesive free installation method perfectly suited to SPC's unique properties.



Figure 4

Uniclic is a premium, patented locking system for SPC flooring that is superior to generic click lock options primarily due to its stronger, more stable joints, grater installation, flexibility and proven reliability over time. While many SPC floors have a click lock system, Global vinyl we use this specific, European high end patented design for our SPC floorings.

Trending of SPC

SPC flooring is highly versatile and can be installed on almost any subfloor, including concrete, ceramic tiles, or wood. Also, these floorings can be used on walls, and it has become a popular design trend. Rigid core technology ensures the floor remains stable in both wet and dry environments. Its waterproof, chemical resistant, and impact proof nature makes SPC a perfect choice for high traffic and high moisture environments.

- **Offices and showrooms**



Figure 5

- **Homes (living rooms, bedrooms, kitchens, bathrooms)**



Figure 6

- **Hotels and restaurants**

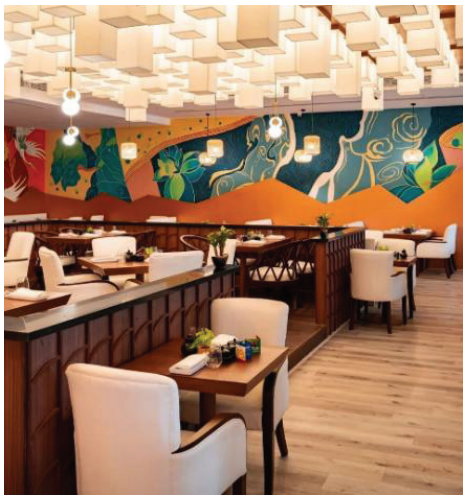


Figure 7

- **Wall installed SPC floorings**

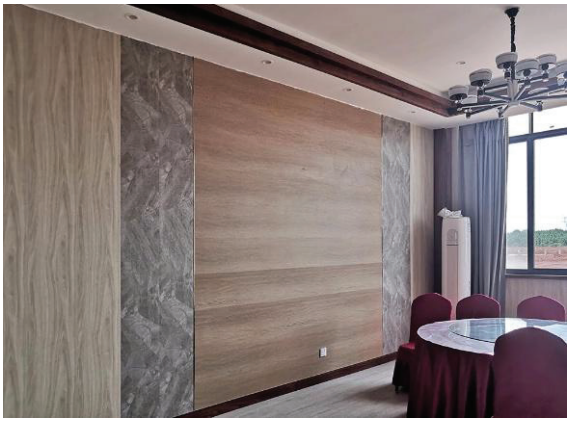


Figure 8

Research and Development Side of SPC

SPC is manufactured under strict international standards to meet export requirements. During production, several critical properties are carefully monitored.

✓ Dimensional Stability (ISO 23999)

SPC does not expand or contract significantly with temperature changes.

✓ Deformation Resistance (ISO 178)

It quickly recovers from impact and heavy loads.

✓ Bonding Strength (ISO 4587)

Advanced processes ensure strong adhesion between layers.

✓ Thickness Options

Higher thickness provides more durability and impact resistance.

✓ Chemical Resistance (ISO 2812)

SPC resists common household chemicals such as detergents, vinegar, grease, and oil.

Recyclable Product

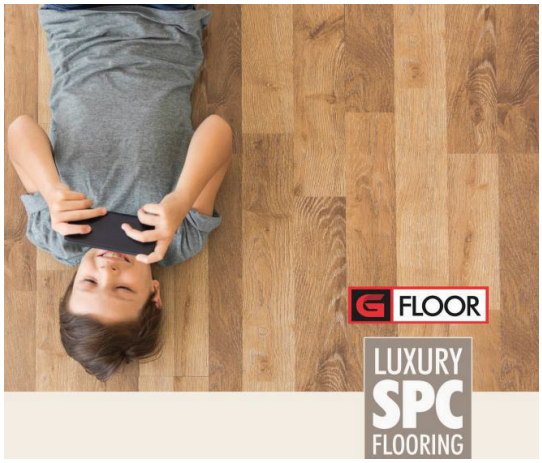
SPC flooring is a 100% recyclable product. Scrap and process waste generated during production can be reprocessed into new SPC boards, making it an ecofriendly flooring choice for the modern consumer.



Figure 9

About Our Company

With decades of experience in the PVC and flooring industry, our company is a leading manufacturer of SPC and LVT flooring. We produce high quality, ecofriendly flooring products that meet international REACH and ROSH standards, ensuring durability, sustainability, and customer satisfaction.



A Review of Blooming in Natural Rubber Products: Mechanisms, Challenges, and Solutions

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Introduction

According to the IUPAC, the definition of blooming is "the process in which one component of a polymer mixture, usually not a polymer, undergoes phase separation and migration to the external surface of the mixture" (Nouman et al., 2017). Chemical additives such as, vulcanizing agents, accelerators, activators, antioxidants, fillers, plasticizers and pigments are incorporated into rubber to obtain desired properties, durability, stability, strength, and performance. However, migration of those components to the surface of a rubber article has a considerable effect on the quality of the product. The bloomed chemicals are visible as a white powder deposit or a greasy liquid or a layer of wax on the product surface (Nouman et al., 2017; Pajarito & Arabit, 2016; Sharj et al., 2020).

Additives like sulphur, accelerators, activators, and fillers bloom as powders while plasticizers and lubricants bloom as oils. Blooming occurs when the concentration of additives exceeds their solubility limit. It can happen before, during or after vulcanization or when storing the rubber product. This process can be influenced by the processing, storing and service temperature of the article. For example, those additives are soluble at the processing temperature and when the product reaches room temperature or less storage temperatures, the additives can get oversaturated and migrate through the rubber matrix and will form a crystalline layer on the surface (Andries et al., 1975).

Effects of Blooming on Products

Sulfur Bloom

Based on literature, the commonly used curatives such as sulfur, sulphanaimide accelerators and sulfur doners diffuse quite readily across a rubber-to-rubber interface (Ignatz-Hoover et al., 2003). Migration of sulfur and other additives to the surface can reduce the adhesion properties and tackiness of rubber compounds (Saeed., et al, 2011); and when vulcanized, because of crosslink gradient, those products will not satisfy the expected durability (Jurkowski & Jurkowska, 1998). Also, coating adhesion and lamination peel strength can be decreased due to the inability of sealing the surface (Datta, et al., 2007). Moreover, discoloration and poor appearance of the products can result in blooming (Yasin et al., 2015). It is a drawback when marketing those products. Although blooming is often viewed as a disadvantage, it can also act as a protective layer on vulcanized rubber providing more resistant to aging in service conditions (Kuzminskiĭ et al., 1962).

Wax Bloom

Wax (petrolium wax) blooms and acts as a physical barrier against ozone attack and this is an advantage to protect rubber products from ozone attack (Dimauro et al, 1979). Blooming antiozonants at the surface is undesirable because it will lead to loss of considerable amount of antiozonant (Ignatz-Hoover et al., 2003).

Blooming Mechanism

Blooming is a diffusion-driven process (Yasin et al., 2015). It occurs when a partly soluble low molecular weight additive is added into a rubber compound at concentrations exceeding its solubility limit, leading to its migration to the surface (Ignatz-Hoover et al., 2003). When the surface of the rubber product crystallizes, a concentration gradient forms between the inner rubber matrix and the subsurface layer. This gradient drives the continued migration of the additive towards the surface until its concentration throughout the material drops below the solubility limit, thereby halting the blooming process (Ignatz-Hoover et al., 2003).

Factors Influence the Blooming

The rate of blooming increases with temperature due to the enhanced rate of diffusion. In the case of sulfur blooming, insoluble sulfur begins to migrate once it reverts to its soluble form, a transition that starts at approximately 110 °C (Ignatz-Hoover et al., 2003). At temperatures above 130 °C, all the sulfur converts

into its soluble form, eliminating any difference in migration behavior between soluble and insoluble sulfur. Therefore, using insoluble sulfur in sulfur-based compounding systems processed at temperatures below 110 °C can help prevent sulfur migration (Ignatz-Hoover et al., 2003).

Conversely, as temperature decreases, the solubility of certain additives, such as waxes, also decreases. This reduction in solubility leads to an increased tendency for blooming (Datta et al., 2007). Additionally, in non-sulfur vulcanizing systems, a higher crosslink density has been shown to influence and increase the blooming rate (Yasin et al., 2015).

Recent Studies on Blooming

In 2019, Yasin et al. identified paraffin wax as the dominant blooming ingredient when natural rubber compounds were tested under varying loadings of dicumyl peroxide (DCP). The blooming substances were analyzed using Energy-Dispersive X-ray (EDX) spectroscopy and Fourier Transform Infrared (FTIR) spectroscopy. Their findings indicated that higher peroxide loadings did not significantly reduce the amount of blooming. On this study, separate FTIR spectrums were analyzed for DCP and other additives. But a controlled vulcanized sample was not tested. They have varied DCP concentrations only for three samples. By including more formulations with varying the concentrations of DCP, more comprehensive study can be executed. Also, the crosslink density was mentioned in the paper, but it has not been measured. The blooming amounts of samples were tested over two weeks to study the actual behavior of blooming yet only tested in ambient storage conditions. The study does not address the blooming behavior in elevated temperature conditions. Also, the study shows the variation of bloom mass over time but has not done a statistical treatment on the mass.

Pajarito and Arabit (2016) studied the relationship between the physical properties of natural rubber vulcanizates and blooming. They used two surfactants—cocamide DEA and glycerol monostearate (GMS)—in the rubber formulation. Blooming was measured before and after thermal aging at 50 °C, over 20 days using a weight-based method. Results showed that all formulations exhibited increased blooming after aging. As blooming increased, modulus also increased, while tensile strength, strain, and tensile set decreased. The study concluded that the deposited bloom on the surface contributes to resistance against deformation, thereby increasing stiffness. Here the samples were prepared using Taguchi L12 design, which leads to study multiple factors with a smaller number of trials. This study shows comprehensive statistical correlations between physical properties and blooming but lacks in molecular level explanations, surface morphology for the identification of bloomed materials and bloom composition. Here the amount of bloom has been measured using adhesive tapes. For more prices bloom measurement, a gravimetric or imaging-based quantification can be used.

In 2016, Santiago et al. investigated ambient blooming behavior in vulcanized rubber using ATR-FTIR and kinetic curve analysis. Using Taguchi L12 method, they examined how different ingredient loadings affect the rate and amount of blooming, as well as both tensile and compression properties. Anyway, Dynamic Mechanical Analysis and Fatigue tests could have been done beyond the above properties. The study showed that high loadings of stearic acid, paraffin wax, and oil increased the blooming rate, while high loadings of sulfur and coco DEA reduced it by enhancing crosslink density and filler dispersion. Increased sulfur also improved mechanical properties, whereas high amounts of oil and zinc stearate softened the rubber and reduced its strength. The study identified a non-Fickian bloom mechanism, with two distinct blooming rates observed. This study offers a good explanation on blooming behavior of rubber vulcanizates especially with non -ionic surfactants. Use of FTIR and kinetic modeling has provided evidence of non fickian diffusion. However, the limitation of replicates per sample can constrain the statistical power of the results. On this study, the samples were aged under ambient temperature for a long period of 64 days and the blooms were tested to show case the actual behavior. But using slightly elevated conditions can indicate real aging more accurately.

Yasin et al. (2015) examined the impact of compounding ingredients and peroxide loading on bloom formation in natural rubber. Among the six formulations, high wax content with 6 phr peroxide showed the highest blooming, while ZDEC with 1 phr peroxide showed the least. Statistical reliability could have been increased by increasing the replicates from each sample. In this study, the bloom has been only analyzed qualitatively by scrapping the surface of the sample. But FTIR could be used to analyze the bloom both quantitively and quantitively. The bloom texture and the distribution could be studied by adding Scanning Electron Microscopy (SEM) imaging. It's a good initiative that they have considered the crosslinking density as well. The study highlighted how both additive type and crosslink density influence blooming behavior. Also

lack of kinetic modeling has been limited the theoretical depth.

Saeed et al. (2013) investigated the effect of sulfenamide accelerator (TBBS) migration and re-agglomeration on the mechanical properties of natural rubber. By varying TBBS and ZnO loadings, it was allowed for a clear attribution of blooming effects only on those additives. Variation of other ingredients could broaden the study area. In this study they found that reduced TBBS blooming enhanced toughness and cyclic fatigue life. Bloom formation and internal structure were analyzed via SEM, while FTIR confirmed the blooming components. Apart from the blooming and fatigue, study has been focused on the variation of viscosity, hardness and the cure characteristics depending on the phr of TBBS and ZnO as well. Not using a mathematical model is a drawback of the study.

Blooming in natural rubber, caused by the migration of additives like curatives to the surface, negatively affects material properties such as hardness and fatigue life. Ansarifar et al. (2010) showed that TBBS blooming increases surface hardness and reduces cyclic fatigue life by over 100%, but lowering the TBBS to ZnO ratio can effectively eliminate this issue.

Huang et al. (2019) demonstrated that adding graphene oxide (GO) to natural rubber latex reduces blooming by forming a dense barrier and capturing excess additives through GO's oxygen-containing groups, thereby protecting the surface and reducing damage. These studies highlight effective methods to control blooming and improve rubber performance. The study has the novelty over the past studies done on blooming while showing innovative solution for the blooming issue. Comprehensive characterization has been conducted by using advanced analytical instruments such as SEM, quartz crystal microbalance (QCM), Energy Dispersive X- Ray (EDX) and Raman spectroscopy. The blooming was assessed under natural environmental conditions to add an ecological relevance. Anyway, this study could include other nano fillers to get more comparative results to highlight the GO performance. Also using a FTIR spectroscopy could provide more data on chemical changes on the surface. By addressing the compatibility with production methods, scalability and cost effectiveness of incorporating GO , could be beneficial to the industry.

Future Directions

When referring to the recently published available studies, it is obvious that there have not been many investigations done focusing on NRL products. Therefore, conducting such studies can be consequential for the industry. Especially focusing on GO incorporation on NRL can be beneficial to the industry. Also, the effect of blooming on the physical and chemical properties of NRL films, dependency of blooming on environmental factors, and sustainable solutions for blooming, can be further investigated.

Conclusion

In conclusion, according to the above studies, blooming shows both Fickian and non Fickian mechanisms with different compounding compositions. Paraffin wax has a high tendency to bloom. TBBS, oils also considerably contribute to the amount and rate of bloom. The addition of peroxide does not influence the decreasing of blooming. Thermal aging can speed up blooming and decrease tensile strength, strain and increase modulus. Blooming can be eliminated by reducing accelerator, activators ratio in rubber vulcanizates. The blooming issue in natural rubber latex films can be inhibited by incorporating even into very low amounts of graphene oxide.

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Developing Clear Career Pathways for the Rubber and Plastics Sector Workforce in Sri Lanka

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Abstract

The rubber and plastics industry is a vital component of Sri Lanka's manufacturing sector, contributing significantly to export earnings and employment. However, the industry faces critical challenges in workforce development, particularly due to the absence of clear career pathways for vocationally trained personnel beyond the National Vocational Qualification (NVQ) Level 6. While the Sri Lanka Qualifications Framework (SLQF) outlines potential bridging mechanisms, their practical implementation remains limited, leaving skilled workers without opportunities for higher education or professional advancement. This gap restricts innovation and weakens workforce retention. Drawing on both the best national and international practices, this paper argues for urgent reforms led by the University Grants Commission (UGC) and the Tertiary and Vocational Education Commission (TVEC). By integrating vocational and academic routes, upgrading competency standards and curricula, and fostering industry collaboration, Sri Lanka can develop a sustainable education to career-pipeline for the rubber and plastics which is commonly referred to as the polymer sector. Such reforms are aligned with Sustainable Development Goals ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all.

Introduction

The rubber and plastics (polymer) industry is a key pillar of Sri Lanka's manufacturing sector, contributing significantly to domestic production, employment generation, and export earnings (Export Development Board, 2022). This industry has long been recognized as a cornerstone of the nation's industrial base, with products ranging from tires and gloves to packaging and engineering plastics being exported to high-demand international markets. As global industries move towards advanced manufacturing, automation, and sustainability, Sri Lanka must ensure that its workforce is not only abundant but also equipped with the skills, adaptability, and innovation required to remain competitive (Varaprasad, 2024; Federal Ministry of Education and Research [BMBF], 2019).

Despite its importance, the rubber and plastics sector in Sri Lanka remains largely labor driven, depending heavily on a workforce with practical skills and applied knowledge to operate machinery, maintain quality standards, and adapt to new technologies. The ability of the industry to remain competitive in the global market will increasingly rely on its human capital. However, a critical weakness undermines the sector's potential with the absence of a clearly defined career pathway for vocationally trained workers to progress into higher levels of education and professional development.

Although entry- and mid-level training opportunities exist within Sri Lanka's vocational training system, the progression from mid-level roles to technologists and professionals is poorly structured (Haikin, 2015). This systemic gap produces a workforce that is technically competent but unable to access advanced qualifications, research opportunities, or leadership roles, thereby weakening long-term industry competitiveness. Addressing this challenge is also central to Sustainable Development Goal 4 (SDG 4), which emphasizes inclusive and equitable quality education and lifelong learning opportunities for all (United Nations, 2015). Aligning Sri Lanka's vocational and higher education systems with these global priorities will be essential for building a future-ready workforce in the polymer industry.

Current Training Opportunities and Their Limitations

At present, the Plastics and Rubber Institute of Sri Lanka (PRISL) plays a pivotal role in offering training programs that advance up to National Vocational Qualification (NVQ) Level 6. These programs equip trainees with valuable technical skills and supervisory-level competencies, bridging the gap between shop-floor operations and mid-management responsibilities. NVQ Level 6 is officially recognized as equivalent to a Higher

National Diploma, reflecting its rigor and relevance (University Grants Commission [UGC], 2015).

However, beyond NVQ Level 6, there is no structured mechanism for vocationally qualified personnel in the polymer sector, to progress further into degree-level or postgraduate qualifications. This creates a ceiling effect where individuals with the potential to contribute more meaningfully to the industry are unable to advance beyond mid-level roles.

The Sri Lanka Qualifications Framework (SLQF) is designed to bridge vocational qualifications with academic programs (University Grants Commission [UGC], 2015). In practice, however, these pathways remain underdeveloped and unclear. Universities frequently do not recognize NVQ Level 6 as an adequate lateral entry qualification, and the absence of consistent policies for recognizing prior learning and professional experience further limits progression. Without reforms to strengthen these pathways, vocationally trained individuals remain confined to mid-level qualifications, preventing industry and the country from fully leveraging their potential for growth and innovation.

The Problem of Brain Drain

Another pressing issue facing the industry is the retention of highly qualified personnel. Graduates who enter the rubber and plastics sector frequently migrate abroad or shift to other industries offering better career prospects, salaries, and working conditions. This phenomenon of "brain drain" is well documented in Sri Lanka's broader economy (Perera & Weerakkody, 2020). The effects on the rubber and plastics sector are particularly damaging. When graduates leave, the sector loses individuals who could have served as research leaders, innovators, or industrial managers. The result is a widening of skills gap. At one end, there is a considerable number of entry-level workers, while at the other, there is a shortage of advanced professionals capable of driving innovation and efficiency.

By contrast, vocationally trained workers are more likely to remain in the industry if they are provided with clear career pathways that allow them to upgrade their qualifications and advance professionalism. Expanding opportunities for such workers to progress into degree programs could therefore help mitigate brain drain, fostering a more loyal and stable workforce while simultaneously strengthening the sector's capacity for growth and innovation. This makes it even more urgent for national education bodies to take corrective measures

Why UGC and TVEC Must Act

The University Grants Commission (UGC) and the Tertiary and Vocational Education Commission (TVEC) must take decisive leadership to bridge the divide between vocational and academic education in Sri Lanka. Their coordinated action is critical for building a skilled workforce capable of meeting the evolving needs of the polymer sector.

As the regulator of higher education, the UGC should establish flexible entry routes for vocationally qualified individuals into degree programs. NVQ Level 6 holders should be granted structured pathways into university degrees, with recognition of prior learning to avoid unnecessary duplication of study. Such measures would promote equality of esteem between academic and vocational routes, motivate learners, and enrich universities with students bringing practical, hands-on expertise (University Grants Commission [UGC], 2015).

Meanwhile, TVEC, as the custodian of vocational education, must not only expand and upgrade National Competency Standards (NCS) in polymer technology and related fields, but also ensure that these standards align with higher-level academic programs. A new curricula and syllabi at the University of Vocational Technology (UNIVOTEC) should be developed to offer Level 7 degrees (bachelor's level) that upgrades vocational training in polymer fields. Collaboration between TVEC, UNIVOTEC, and industry is essential to design programs that reflect current industrial needs, including sustainability practices, advanced polymer processing, digital manufacturing, and innovation management (Gunawardena, 2017; Green & Steedman, 2003).

Without coordinated action from both bodies, Sri Lanka risks maintaining a fragmented education system where vocational and academic streams operate in parallel without meaningful integration. This issue not only limits opportunities for learners but also weakens the capacity of the polymer sector to remain competitive in global markets. Expanding pathways into degree programs will create a more loyal and skilled workforce, reduce brain drain, and support lifelong learning and upskilling initiatives (Perera & Weerakkody, 2020).

The Role of Industry

The industry itself cannot remain passive in this transformation. Employers, professional bodies, and experts in the polymer sector must play an active role

in shaping vocational education. Their engagement with TVEC as assessors, advisors, and curriculum developers is vital to ensure that training programs remain relevant to industry realities and emerging technological trends.

Moreover, industry stakeholders must exert pressure on TVEC and UGC to act coordinately. By demonstrating the economic importance of the sector and the costs of inaction. The industry can help ensure that the development of clear career pathways becomes a national priority.

International experience demonstrates that effective vocational education and training systems require close collaboration between governments, employers, and training providers, with strong alignment to labor market needs and opportunities for progression into higher education (Eichhorst et al., 2012). Embedding such collaboration within Sri Lanka's polymer sector would not only strengthen workforce development but also enhance global competitiveness.

Way Forward

To build a sustainable and empowered workforce for the polymer industry, the following steps are essential.

- Expand NVQ pathways beyond Level 6 by developing degree-level programs (NVQ 7) in Polymer Technology, which can be offered and administered by PRISL and the University of Vocational Technology (UNIVOTEC).
- Clarify and implement SLQF bridging mechanisms, enabling vocational qualifications to progress smoothly into degree programs with recognition of prior learning.
- Encourage UGC involvement by opening flexible entry opportunities for vocationally qualified individuals into universities, creating equality of esteem between vocational and academic routes and promoting lifelong learning.
- Strengthen TVEC's role in upgrading comprehensive National Competency Standards (NCS) in Polymer Technology that reflect evolving industry needs, including sustainability and advanced technologies.
- Encourage industry experts to be involved as assessors and advisors in vocational assessments, curriculum design, and quality assurance to maintain relevance and credibility.
- Promote collaborative projects between universities, PRISL, and industry to foster applied research in polymer technology, providing vocational graduates with opportunities to contribute to innovation.
- Raise public awareness of vocational pathways, highlighting success stories of NVQ graduates who progress to higher roles, thereby increasing the attractiveness of vocational education.
- Learn from international best practices such as Germany's dual training system (Federal Ministry of Education and Research [BMBF], 2019), Singapore's seamless vocational-to-degree transitions (OECD, 2020), and Malaysia's TVET–university integration (Rajah & Ting, 2018), providing evidence that Sri Lanka can build an effective and inclusive framework tailored to its industrial needs.

Conclusion

The vocational training system provides a solid foundation at the entry and mid-levels of rubber and plastics sector workforce, the absence of clear pathways into higher education and professional advancement remains a critical weakness. Unless this gap is addressed, the industry will have continue to struggle with brain drain, skills shortages, and limited innovation capacity.

The University Grants Commission and the Tertiary and Vocational Education Commission hold the keys to solving this challenge. By fostering flexible entry routes, upgrading competency standards, forming curriculum for degree levels, and collaborating closely with PRISL, UNIVOTEC, and industry stakeholders, can build a coherent education-to-career pipeline (UGC, 2015; TVEC, 2018). Such a system would not only empower individuals but also ensure the long-term sustainability of one of Sri Lanka's most important manufacturing sectors.

Global experience shows that this is both possible and practical. Germany's dual vocational training model Singapore's seamless vocational-to-degree pathways and Malaysia's alignment of TVET with higher education demonstrate that clear career structures can retain talent, foster innovation, and strengthen industry competitiveness. Sri Lanka must adapt these lessons to its own context, using them as a roadmap for reform.

The time for action is now. If Sri Lanka is to remain competitive in the global rubber and plastics market, UGC and TVEC must prioritize the creation of clear, practical, and inclusive career pathways. This is not merely an educational reform; it is an economic necessity for the future of the nation. Ultimately, investing in clear career pathways is not only an educational reform but

also a commitment to sustainable industrial growth and alignment with global development goals.

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A Materials Science-Based Evaluation of Pet Bottle Recycling: Structural Degradation Analysis Via FTIR Spectroscopy and Shore D Hardness Testing



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Abstract

Polyethylene terephthalate (PET) is a widely used thermoplastic polymer valued for its strength, lightweight nature, and recyclability. However, repeated thermo-mechanical recycling can lead to significant structural degradation. This study investigates the effects of five re-melting cycles on the structural and mechanical properties of post-consumer PET bottles. The objective is to evaluate the extent of degradation using Shore D hardness testing and Fourier Transform Infrared (FTIR) spectroscopy.

PET samples were heated to 300°C at a rate of 10°C/min, held for 20 minutes, and cooled to room temperature. This process was repeated for five cycles. After each cycle, the hardness and FTIR spectra were recorded. The results showed a consistent increase in Shore D hardness, rising from 80 in the first cycle to 83.5 in the fifth, indicating increased brittleness due to polymer chain scission and crystallinity growth. FTIR analysis revealed reductions in peak areas and shifts in characteristic vibrational bands such as the carbonyl stretch (from 1400 to 1100 cm^{-1}) and weakening of C–H and O–C–C functional groups.

These changes confirm progressive degradation of the PET structure, with an estimated 8.92% reduction in structural integrity per cycle. The findings support the concept of downcycling, where recycled PET loses quality and becomes suitable only for lower-grade applications. Although PET can be recycled mechanically, the absence of additives or stabilizers accelerates degradation, limiting reuse in high-performance products.

This study did not include molecular weight analysis, crystallinity (DSC/XRD), or tensile strength testing. Future research should explore these parameters and evaluate the role of additives in enhancing recyclability.

Keywords: PET, re-melting, thermal degradation, FTIR spectroscopy, Shore D hardness, downcycling

1. Introduction

Polyethylene terephthalate (PET) is one of the most widely used plastics, especially in beverage bottles and food packaging, due to its strength, lightweight nature, and the recyclability. However, growing accumulation of PET waste is a concern due to its non-biodegradable nature and long-term environmental impact (Ashish et al., 2023).

Recycling PET (rePET) has become an essential environmental strategy, and various methods such as mechanical, thermo-mechanical, chemical, and energy recovery processes have been investigated (B. Geyer, et al., 2016). However, studies have shown that repeated processing of PET can lead to deterioration in its mechanical and chemical properties due to thermal degradation, and hydrolysis (Jankauskaitė, V. et al., 2008). These degradation pathways affect the polymer's molecular weight, viscosity, and mechanical integrity—ultimately leading to downcycling, where the recycled material becomes suitable only for lower-grade applications (Altun & Ulcay, 2004).

While extensive research has been conducted on the development of PET recycling methods, there remains a research gap concerning the quantitative assessment of structural and mechanical degradation in PET across multiple re-melting cycles, especially using combined techniques such as Fourier Transform Infrared (FTIR) Spectroscopy and Shore D hardness testing. This

study aims to investigate the structural and mechanical degradation of PET during successive thermal recycling cycles using Shore D hardness testing and FTIR spectroscopy.

By focusing on hardness testing in conjunction with FTIR analysis, this research offers a practical and technically grounded approach to evaluating downcycling behavior in PET without the need for more complex mechanical tests. The data derived from hardness shifts and FTIR spectra reveal meaningful trends in material performance over multiple recycling cycles

The limitations of this research are the absence of molecular weight measurements (e.g., via GPC), crystallinity analysis (e.g., via DSC or XRD), and tensile strength data. This focused methodology lays the groundwork for future investigations that may include chemical stabilizers, additives, and advanced characterization techniques to develop more comprehensive degradation models.

While tensile strength or molecular weight measurements could offer deeper mechanical insight, this study focuses on Shore D hardness as a rapid and practical measure of surface rigidity, which serves as a proxy for structural changes due to chain scission and crystallinity increases. The choice was guided by the aim to evaluate degradation with minimal equipment and under conditions accessible in most polymer laboratories. FTIR spectroscopy was used in tandem to assess changes in functional groups, offering a holistic yet accessible degradation profile of reprocessed PET.

2. Literature Survey

PET is a hard, liner semi-crystalline thermoplastic polymer, is among the fastest-growing industrial polymer. Its widely used in packaging application, due to chemical stability, mechanical strength, and cost-effectiveness. Transparency reduction in recycled PET has been noted as a limitation in food-grade reuse, attributed to increased crystallinity and chain scission during thermal reprocessing (Geyer et al., 2016; Awaja & Pavel, 2005). The recycling of post-consumer PET (pcPET) is an inherently cross-disciplinary process, encompassing fields such as polymer chemistry, materials physics, process engineering, and manufacturing technology (Awaja & Pavel, 2005).

Mechanical re-melting is a common method to rePET (Awaja & Pavel, 2005), but repeated cycles cause degradation. Heat and moisture break ester bonds through hydrolysis, forming hydroxyl and carboxyl end groups. Thermal degradation produces volatile compounds and accelerates chain scission, reducing molecular weight and altering mechanical properties (Altun & Ulcay, 2004; Girija, B., et al., 2005; Bikiaris, D. N., et al., 1999). As a result, additives like antioxidants or processing aids are often required to restore its quality due to reduces of hydrolytic and thermomechanical degradation (Jankauskaitė, V. et al., 2008, Awaja & Pavel, 2005). Studies show that with each re-melting cycle, PET becomes harder and more brittle due to the formation of shorter, more crystalline chains.

Fourier Transform Infrared (FTIR) Spectroscopy is commonly used to analyze PET structure. Specific peaks, such as the carbonyl stretch C=O Stretching (~1714–1730 cm^{-1}), C–O–C Stretching (~1240–1100 cm^{-1}), C–H Bending (~1400–1000 cm^{-1}), Aromatic Ring Vibrations (~1500, 871, 722 cm^{-1}), weaken with repeated reprocessing, indicating structural loss (Vijayakumar & Rajakumar, 2012).

Shore D hardness testing offers a reliable method to detect surface hardening in polymers with increasing crystallinity and brittleness during reprocessing (ASTM D2240, 2021; Altun & Ulcay, 2004) as rigidity and brittleness that are key indicators of polymer degradation resulting from chain scission and increased crystallinity during re-melting (Altun & Ulcay, 2004).

3. Methodology

The experiment followed a mechanical reheating approach, using commercial pcPET bottles subjected to five thermal cycles under controlled moisture conditions without additives or stabilizers. This number of cycles reveals meaningful trends without causing total material breakdown.

Prior to heating, all batch pcPET bottles were thoroughly cleaned and dried, and cut into flakes approximately 10–15 mm in size. No additives or stabilizers were used. Each batch (~100 g) was subjected to five successive remelting cycles at 300°C for 20 minutes in a muffle furnace, with heating at 10°C/min and natural air cooling to ambient temperature between cycles.

The selection of 300°C was intended to simulate accelerated degradation while ensuring complete melting; it exceeds PET's typical processing temperature but remains below its decomposition onset. Five cycles were chosen to balance observable degradation against physical specimen integrity (Bikiaris & Karayannidis, 1999).

Hardness was measured on solidified disk specimens (approx. 3 mm thick, 25 mm diameter) molded using a steel die. Each sample underwent five readings on different surface regions using a calibrated Shore D durometer in accordance with ASTM D2240, and values were averaged. Standard deviation was <1% of the mean.

For FTIR, each specimen was microtomed to ~200 µm thickness and scanned from 4000–500 cm^{-1} using a Bruker TENSOR 27 FTIR spectrometer. Spectra were baseline corrected and normalized to a common reference peak. Peak area changes and shifts in key vibrational bands in the C=O and O–C–C regions were calculated using OPUS software to quantify functional group degradation. These spectral features were quantitatively analyzed to estimate the hardness and percentage loss of functional group integrity per cycle, offering a novel quantification of degradation progression.

4. Results And Discussion

4.1. Hardness analysis

Hardness increased with each re-melting cycle, rising from 80 (Cycle 1) to 83.5 (Cycle 5), a 1.095% increment per cycle. Shore D hardness values increase as flexibility decreases, indicating material stiffening, a process known as downcycling (e.g., Figure 1). Repeated remelting makes PET harder while simultaneously degrading the material through thermal chain scission. (e.g., Figure 6). This mechanical stiffening reflects increased crystallinity and chain shortening, consistent with hydrolysis and thermal degradation (Jankauskaitė, V. et al., 2008; Awaja & Pavel, 2005).

4.2. FTIR spectral analysis

The FTIR transmission spectrum illustrated the reference PET sample and the pcPET sample taken from

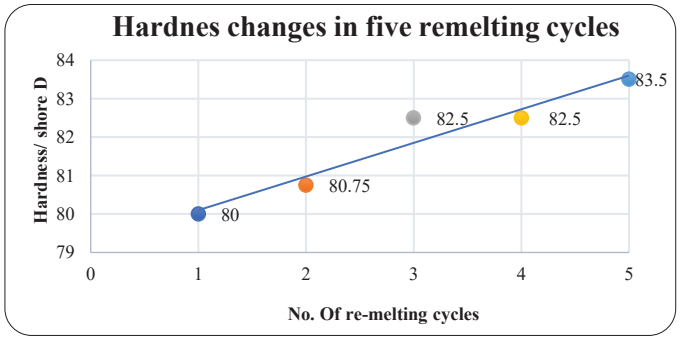


Figure 1: Hardness across the five remelted samples

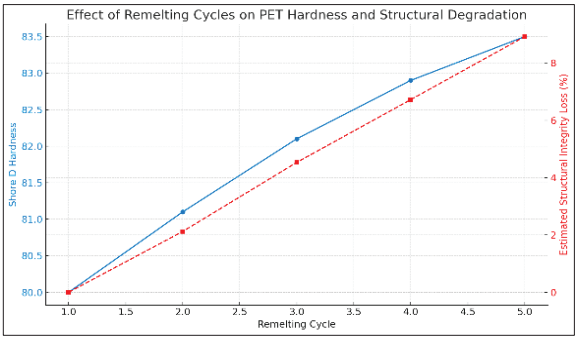


Figure 2: The relationship between remelting cycles, Shore D hardness, and estimated structural integrity loss

the experiment. The spectra exhibit strong concordance, indicating the compounds are structurally and chemically analogous (e.g., Figure 2).

FTIR spectra revealed significant shifts in peak positions and reduced peak areas in key vibrational modes: C=O stretching shifted from 1730 to 1714.2 cm^{-1}, indicating ester bond weakening; C-H and O-C-C bonds exhibited decreased peak areas, especially at 1010 and 1081 cm^{-1} within five melting cycles. Aromatic groups (722.1, 871.5, and 1505 cm^{-1}) retained identifiable signals, but their intensities diminished with each cycle (e.g,.Figure 3,4).

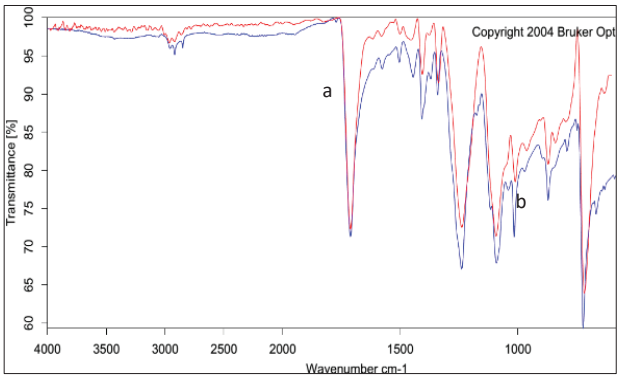


Figure 3: FTIR spectrum of the (a) reference PET sample and (b) pcPET experiment sample

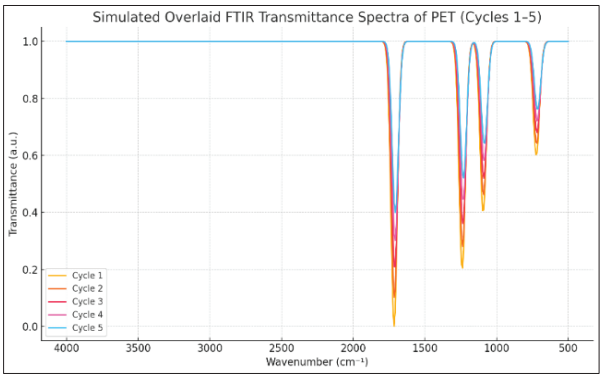


Figure 4: FTIR transmittance spectra for PET across five remelting cycles

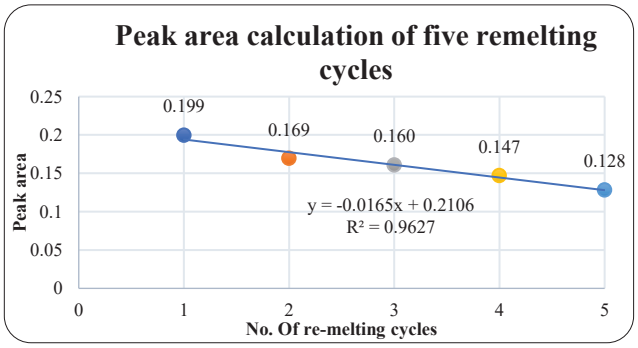


Figure 5: Area calculation of C-H and O-C-C in five remelting cycles

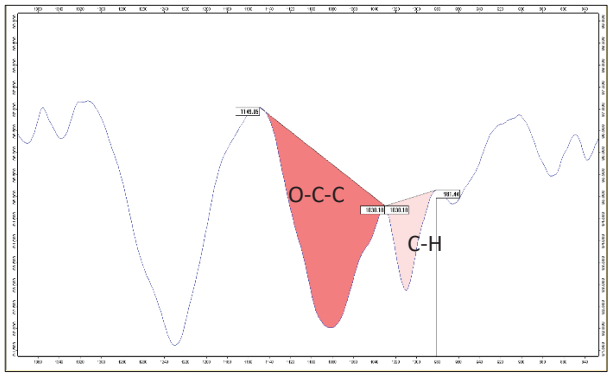


Figure 6: Area calculation of C-H and O-C-C bonds

FTIR analysis indicates an estimated 8.92 % structural integrity loss over per cycles (e,g., Figur 4, 5). The rise in carboxyl end groups and low molecular weight oligomers further confirms progressive thermal degradation during reprocessing (Bikiaris et al., 1999).

The progressive increase in Shore D hardness and the FTIR-detected peak shifts confirm that remelting PET without stabilizers leads to consistent physical stiffening and molecular degradation, demonstrating a direct link between thermal exposure and polymer chain breakdown.

5. Conclusion

Successive thermal remelting cycles of PET lead to measurable increases in surface hardness and corresponding degradation of molecular structure. Shore D hardness values increased at an average rate of 1.095% per cycle, indicating progressive embrittlement and rigidity. FTIR analysis revealed a ~8.92% loss of functional group integrity per cycle, as evidenced by reduced peak areas in ester (C=O) and ether (O–C–C) bonds.

These results confirm the trend of downcycling in mechanically recycled PET, linking thermal exposure directly to molecular degradation. While Shore D and FTIR offer effective first-order characterization, further studies incorporating tensile strength, molecular weight analysis, and crystallinity evaluation (e.g., via DSC or XRD) are recommended to build a more comprehensive model of PET recyclability.

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The Modern Laboratory as a Socio-Technical System: Leadership, Quality, and Innovation in Practice

Devaki Rodrigo

Abstract

Modern laboratories have evolved from controlled experimental spaces into complex socio-technical systems that combine human creativity, management strategy, digitalization, and quality assurance. They now serve as strategic ecosystems that drive innovation, compliance, and scientific credibility. This paper highlights how leadership, quality culture, and innovation intersect to enhance performance. Rooted in socio-technical systems theory, this approach emphasizes the interplay among people, processes, and technology. Key factors include adaptability, emotional intelligence, sustainability, and a commitment to continuous improvement. Viewing nonconformities as learning opportunities, laboratories achieve excellence by blending technical precision with human insight, creating resilient, self-learning, and ethically driven systems for the future.

Keywords: Laboratory management, Socio-technical systems, Quality assurance, Leadership, Innovation, Sustainability, Laboratory 4.0

1. Introduction

Modern laboratories have transitioned from conventional experimental settings to integrated systems that harmonize human expertise, technological capabilities, and managerial strategies. They are no longer limited to producing test results but play a vital role in driving innovation, ensuring compliance, and maintaining trust in science and industry. Today's laboratories operate as socio-technical ecosystems, where technical tools, data systems, and skilled professionals collaborate toward shared goals. Effective leadership and a strong quality culture are key to this transformation, shaping how laboratories adapt to change and maintain high standards of performance. Managers now balance scientific knowledge, digital technologies, and strategic planning to build efficient, ethical, and sustainable laboratories. At the same time, collaboration, communication, and emotional intelligence are recognized as essential human factors that support accuracy and reliability. This paper examines the intersection of leadership, quality management, and innovation in shaping the modern laboratory, within a socio-technical framework, highlighting the need for a balance between technical precision and human insight in achieving excellence.

2. The Modern Laboratory: From Curiosity to Strategy

Modern laboratories have evolved from small experimental spaces into dynamic ecosystems integrating science, technology, and management. They now drive innovation, ensure compliance, and enhance industrial competitiveness. Far beyond experimental venues, laboratories function as strategic enterprises blending human creativity with precision systems to advance discovery and support production (Mokhtari & Karimi, 2022).

2.1 From Experimentation to Organization

Early laboratories of the seventeenth and eighteenth centuries, led by figures like Boyle and Lavoisier, were curiosity-driven spaces without formal structure. The Industrial Revolution integrated science and commerce, introducing systematic methods, management, and safety protocols. By the twentieth century, laboratories had become vital industrial assets, guided by frameworks such as GLP and ISO standards for reliability and precision (Garcia et al., 2023). Today, Laboratory 4.0 embodies data integration, automation, AI, and sustainability, transforming operations and leadership (Velarde et al., 2021). Modern management now emphasizes strategic direction, balancing innovation, efficiency, and environmental responsibility, thereby establishing laboratories as dynamic centres of excellence and credibility.

2.2 The Laboratory Manager: Scientist, Strategist, and Leader

The laboratory manager plays a central role, connecting science, people, and systems. Since the Industrial Revolution, laboratories have evolved into structured, safety-oriented organizations (Fleck & Bate, 2020). Today's managers balance leadership and technical

expertise, integrating scientific, managerial, and regulatory knowledge (Ongaro et al., 2023). Their duties span operations, quality, compliance, budgeting, and staff development (Parand et al., 2020). They ensure alignment with standards like ISO 17025 and drive innovation through strategic planning. Modern managers act as change agents, interpreting data, managing digital systems, fostering collaboration, and promoting continuous improvement through trust, foresight, and adaptability to ensure sustainable laboratory excellence.

2.3 Core Functions of Management in the Laboratory

The classic management functions —planning, organizing, leading, and controlling —remain central to laboratory operations but have become more strategic and complex. Planning now involves aligning scientific goals with institutional strategy, managing risks, and anticipating disruptions. Organizing requires integrating multidisciplinary teams, clarifying roles, and ensuring efficient communication. Leadership emphasizes inspiration over direction, fostering trust, autonomy, and shared purpose through emotional intelligence and empathy. Controlling focuses on performance improvement, using audits, calibration, and data dashboards to monitor quality and efficiency. Feedback and root-cause analyses turn issues into learning opportunities. Modern management adds a fifth dimension: continuous evaluation, achieved through benchmarking, peer learning, and technology integration, to sustain competitiveness.

2.4 Organizing for Scientific Excellence

A laboratory's structure greatly influences its efficiency and results. Large labs often employ functional structures, grouping experts by discipline for specialization, but this limits opportunities for collaboration. Matrix models blend functional and project-based teams, enhancing flexibility and cross-disciplinary work. Project-based structures are well-suited for rapid innovation, while hybrids strike a balance between control and creativity. Increasingly, networked structures link global labs through digital platforms, enabling data sharing and remote collaboration. The most effective laboratories align their structures with strategic goals, ensuring autonomy, compliance, and operational efficiency. This structural adaptability fosters innovation, accountability, and seamless knowledge exchange across scientific and organizational boundaries.

2.5. The Laboratory as a Socio-Technical Ecosystem

Effective laboratory management views the lab as a socio-technical system where people and technology interact. The technical side encompasses instruments, procedures, and data systems that ensure accuracy, while the social side involves culture, communication, and motivation that drive collaboration. Both must align; an unmotivated worker or faulty tool can harm results. Successful management invests equally in technology and people through training, teamwork, and innovation (Pasmore et al., 2022). This balance fosters resilience, enabling laboratories to adapt to disruptions such as equipment failures or data breaches. Open communication and shared learning further strengthen stability and continuous improvement within modern laboratory environments.

2.6 Leadership and Culture: The Human Side of Science

Leadership is the driving force behind laboratory success, providing purpose and inspiration beyond routine management. Effective leaders foster trust, creativity, and collaboration, adapting their style to the context, participative for engagement and directive in emergencies. Transformational leadership, paired with emotional intelligence, enables calm decision-making, empathy, and ethical judgment. Trust-based cultures foster open communication, encourage learning from mistakes, and promote teamwork. Regular feedback, recognition, and transparency strengthen cooperation and accountability. Modern laboratories thrive not only on advanced instruments and standardized procedures, but also on leaders who nurture talent, align individual and collective goals, and strike a balance between scientific rigor and human-centered management.

2.7 Quality, Strategy, and People: The Pillars of Laboratory Excellence

Reliable laboratory results are built on trust, precision, and consistency. A strong Quality Management System (QMS) transforms these expectations into daily practice, integrating policies, processes, and responsibilities across all activities. Modern laboratories adhere to standards such as ISO 9001, ISO/IEC 17025, and ISO 15189, fostering a culture where staff take ownership, view non-conformities as learning opportunities, and continually improve (Ongaro et al., 2023; Dresch et al., 2022). Documentation, audits, risk-based assessments, and corrective actions ensure transparency, accountability, and reliability. A dynamic QMS transforms compliance into a competitive advantage, enabling the laboratory to become a learning organization that strikes a balance between excellence, credibility, and innovation.

3. Quality Assurance and Quality Control: The Foundation of Reliable Laboratory Results

In any scientific or industrial laboratory, credibility depends on the reliability and precision of the results,

which are achieved through Quality Assurance (QA) and Quality Control (QC). QA provides a structured system of policies, processes, and standards (ISO/IEC 17025; ISO 15189) to prevent errors, ensure consistency, and promote transparency. QC applies these principles in practice by monitoring instruments, analyzing controls, and initiating corrective actions to maintain accuracy. External evaluations, such as Proficiency Testing (PT) and Inter-Laboratory Comparisons (ILC), benchmark performance, identify areas for improvement, and support accreditation. Laboratory managers lead by maintaining systems, ensuring compliance, mentoring staff, and protecting data integrity. Staff responsibilities include following validated methods, recording data accurately, monitoring QC charts, and participating in PT. Together, QA, QC, PT, and ILC form a quality continuum that ensures reliable, reproducible, and ethically sound results. This integrated approach transforms laboratories into trusted sources of scientific truth, safeguarding institutional reputation and advancing knowledge. Reliable laboratory results are the outcome of disciplined systems, skilled personnel, and continuous evaluation, emphasizing that every measurement carries responsibility, integrity, and impact.

Laboratory staff are the hands and minds that turn leadership vision into reliable results. Their responsibilities include following validated methods, maintaining accurate records, monitoring calibration, and ensuring proper sample handling to prevent errors and ensure accuracy. Active engagement in Quality Control, including control charts and proficiency testing (PT), builds technical competence, confidence, and professional pride. Open discussion of PT results fosters learning, continuous improvement, and skill development. Alongside robust QA and QC systems, PT and Inter-Laboratory Comparisons (ILC) ensure results are accurate, reproducible, and credible beyond institutional boundaries. Laboratory managers provide leadership and infrastructure, while staff ensure discipline, precision, and integrity. Together, they foster a culture of accountability, transforming laboratories into trusted sources of scientific knowledge and truth. In today's data-driven world, reliable laboratory results reflect expertise, ethical commitment, and responsibility, safeguarding institutional reputation and upholding the essence of science: truth measured with precision and delivered with trust.

4. Strategic and Financial Stewardship

Running a laboratory requires striking a balance between scientific expertise and financial management. Effective budgeting, covering operations, capital investments, and project costs, ensures sustainability and growth. Cost tracking, preventive maintenance, shared equipment, and bulk procurement optimize resources. Transparent procurement, vendor assessment, and digital inventory systems, often linked to LIMS, maintain efficiency and traceability (Reed et al., 2021). Sustainability is increasingly integrated, with a focus on energy-efficient equipment and eco-friendly suppliers. Strategic financial and resource management ensures high-quality operations, supports staff and equipment needs, and prevents disruptions to operations. By combining fiscal prudence with environmental responsibility, laboratories can thrive while maintaining operational excellence and long-term viability.

4.1 Strategic Planning: From Operations to Vision

Strategic planning elevates laboratory management from routine oversight to visionary leadership. It begins with assessing internal strengths and weaknesses, as well as external opportunities and threats, leading to SMART objectives that are aligned with institutional goals. Implementation requires all staff and projects to connect to the broader mission. Regular reviews and scenario planning for supply shortages, emerging diseases, or disruptive technologies build resilience. Tools like the Balanced Scorecard track financial health, customer satisfaction, process efficiency, and learning, enabling informed decisions. Strategic management ensures that resources, human, financial, and technological, are optimized, fostering agility, innovation, and sustained excellence while keeping the laboratory prepared for change and aligned with its long-term goals.

4.2. The Human Element: Developing Competence and Commitment

A laboratory's success depends as much on its people as its instruments. Human Resource Management (HRM) ensures the right mix of skills through workforce planning, recruitment, and retention. Hiring emphasizes both technical expertise and behavioral traits, such as precision, collaboration, and ethical integrity. Continuous development includes competency-based training in technical skills, quality awareness, data integrity, leadership, and digital literacy, supported by assessments, reskilling, and upskilling. Performance evaluation combines quantitative measures, such as accuracy and turnaround times, with qualitative aspects, including teamwork and innovation, which are reinforced through feedback and recognition. Team development fosters collaboration among scientists, technicians, and support staff, guided by leaders who strike a balance between structure and flexibility. Succession planning prepares future leaders through

mentoring, delegation, and formal training. Even with automation and AI, human skills like critical thinking, empathy, ethical judgment, and adaptability remain essential. Laboratories that invest in their people cultivate expertise, innovation, and continuity, ensuring operational stability and long-term scientific excellence.

4.3. Integrating Quality, Strategy, and People

The interplay between quality systems, strategic management, and human development defines the maturity of a laboratory. Quality provides the structure, strategy gives direction, and people deliver execution. Together, they form a virtuous cycle where learning feeds improvement, improvement strengthens performance, and performance inspires innovation. A high-performing laboratory is therefore not built solely on technology, but on alignment between its mission and method, between systems and staff, and between scientific rigor and managerial insight. When these elements harmonize, the laboratory becomes more than a workplace; it becomes a center of excellence that contributes meaningfully to science, society, and sustainability.

5. Safety, Digital Transformation, and the Future of Laboratory Innovation

If quality and people form the heart of laboratory management, then safety, technology, and sustainability are its living pulse. Together, they define how laboratories operate responsibly, evolve intelligently, and adapt to the demands of a rapidly changing world. In modern institutions, excellence is not measured solely by precision or accreditation, but also by how safely, sustainably, and intelligently laboratories conduct their work.

5.1. Safety and Environmental Stewardship: The Ethical Core

Laboratory activities involve risks from chemicals, biological agents, and high-voltage or pressurized systems. Safety management is both a legal and ethical responsibility, protecting people, the environment, and scientific credibility. Effective systems combine leadership commitment, clear policies, risk assessments, engineering and administrative controls, and personal protective equipment. Incident reporting and investigation turn mistakes into learning opportunities, fostering a blame-free safety culture. Environmental protection, including proper waste management and compliance with standards like ISO 14001, ensures sustainability. Continuous training, effective communication, and visible leadership foster ownership at all levels, making safety an integral part of laboratory discipline, professionalism, and world-class performance.

5.2. Digital Transformation and the Rise of Laboratory 4.0

Laboratory 4.0 transforms labs through automation, connectivity, and intelligence, merging physical processes with digital ecosystems. Central to this is the Laboratory Information Management System (LIMS), which integrates sample tracking, data analysis, and reporting, reducing errors and enhancing efficiency. Robotics, AI, and IoT improve accuracy, productivity, predictive maintenance, and data-driven insights. Dashboards and analytics optimize workflows, while cybersecurity and staff training protect sensitive information. Success depends on both technology and leadership, ensuring teams embrace innovation while maintaining scientific rigor. Laboratory 4.0 streamlines operations, enhances decision-making, and reinforces reliability, safety, and excellence in modern scientific practice.

6. Sustainability and Green Laboratory Practices

Modern laboratories are embracing sustainability, reducing environmental impact while maintaining safety and performance. This approach rests on three pillars: environmental stewardship, social responsibility, and economic efficiency. Energy-efficient HVAC systems, LED lighting, and renewable energy sources reduce consumption. Water-saving systems and green chemistry minimize waste. The "4Rs" of Reduce, Reuse, Recycle, and Recover guide waste management, while sustainable procurement encourages the use of eco-friendly suppliers (Santoro et al., 2022). Certification programs recognize innovation in energy, waste management, and design. Sustainable practices lower costs, enhance efficiency, and demonstrate that scientific excellence and environmental responsibility can coexist, making laboratories safer, greener, and more socially responsible.

7. Innovation, Continuous Improvement, and Future Directions

The laboratories of the future will be defined by innovation and continuous improvement, not just new instruments. Methodologies like Lean, Six Sigma, and Kaizen enhance efficiency, quality, and daily progress (Tian et al., 2023). True innovation requires a mindset of curiosity, experimentation, and openness to change, supported by design thinking and staff-led idea challenges. Effective change management ensures team engagement, clear communication, and early successes. Emerging trends, such as AI, digital

twins, blockchain, virtual labs, and sustainability, are reshaping collaboration, operations, and environmental responsibility. Future laboratory leaders will combine scientific, strategic, and technological expertise, striking a balance between human insight and advanced systems to create efficient, innovative, and impactful laboratories.

8. The Laboratory as an Evolving Ecosystem of People, Processes, and Technology

Modern laboratory management is no longer about managing benches and budgets, it is about leading ecosystems. Laboratories have evolved into living systems that integrate people, technology, quality, and sustainability. Their success depends on striking a balance between innovation and control, speed and safety, and data and ethics. As science continues to expand into new frontiers such as genomics, artificial intelligence, and materials engineering, the laboratory will remain the crucible of progress. However, to sustain its mission, it must continue to evolve. The laboratory of the future will be digital yet humane, automated yet ethical, efficient yet sustainable. Ultimately, excellence in laboratory management is not achieved solely through technology or certification; it is achieved through a culture that values learning, collaboration, and accountability. When that culture takes root, the laboratory transcends its walls, becoming not just a workplace but a model for how science can serve humanity responsibly, intelligently, and sustainably.

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Pushing boundaries! - VESTENAMER® in Recycling Rubber Applications

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ABSTRACT

Recycling rubber is globally gaining traction in efforts towards a circular economy. Beside sustainability aspects, it is also increasingly recognized as a cost-efficient raw material in applications like modified asphalt, virgin rubber blends, and molded goods from ground tire rubber. However, its applicability is limited by performance gaps or processing challenges whenever it is compared to virgin rubber products or polymer materials. The rubber additive VESTENAMER® has proofed to be a valuable tool in overcoming these gaps. We will show latest examples of how trans-polyoctenamer transforms recycling rubber into a valuable resource by improving performance and processing of rubberized asphalt, rubber blends, and molded goods.

INTRODUCTION

Trans-polyoctenamer (TOR) was firstly described by Natta et al. in the nineteen-sixties,1 but it took until the nineteen-eighties to recognize its value as a rubber material.2 Commercialized under the trade name VESTENAMER®, trans-polyoctenamer has first been made available to the rubber industry by Hüls AG, Germany, later part of Degussa, and is today provided by the specialty chemical company Evonik.

TOR provides an unusual set of properties (Table 1) like having partially macrocyclic polymer structure,3 high crystallinity,4,5 a low melting point and glass transition temperature,6,7 high thermal stability,8 as well as the ability to be vulcanized like common rubber polymers. This unique combination of properties makes it a valuable tool in rubber product manufacturing. TOR is typically applied as a component in rubber formulations, and not as a base polymer, due to its very low Mooney viscosity. Typically, 5-15phr of base polymer are replaced by TOR to achieve the desired effects. Many benefits have been described in processing:2,9–11

- Plasticizing in mixing and processing
- Better dispersion
- Improved green strength and dimensional stability
- Compatibility improvements in rubber blends
- Better surface finish and higher extrusion speeds

Some combinations of effects are counter-intuitive and can exclusively achieved by TOR, like plasticizing effect and improving green strength at the same time.12 This “magic behavior“ in rubber applications becomes also visible by many formulation examples where TOR acts as a processing aid (lower Mooney viscosity, improved finish), without compromising and often improving mechanical and dynamical properties of the vulcanizate. Some typical effects by TOR, when introduced into formulations are:

- Hardness is maintained in hard mixtures
- Elasticity is improved
- Less heat build-up under dynamic stress
- Reduced abrasion
- No migration

Property		Method (norm)	Unit	Value
Molecular weight	Mw	GPC (acc. DIN 55672-1)	g/mol	140.000
Glass transition temperature	Tg	DMA (ISO 6721-5)	°C	-67
Crystallinity @23°C		DSC (ISO 11357)	%	~ 30
Melting point (2nd heating)	Tm	DSC (ISO 11357)	°C	54-56
Thermal decomposition		TGA (ISO 11357)	°C	> 400
Double bonds cis/trans ratio		IR (SOP 0188)	%	20/80
Mooney viscosity @100°C	ML (1+4)	DIN 53523, ASTM D 1646	MU	<10
MVR (190 °C, 2.16 kg load)		ISO 1133	cm3/10min	20

Table 1 - Specification and properties of trans-polyoctenamer (VESTENAMER® 8012)

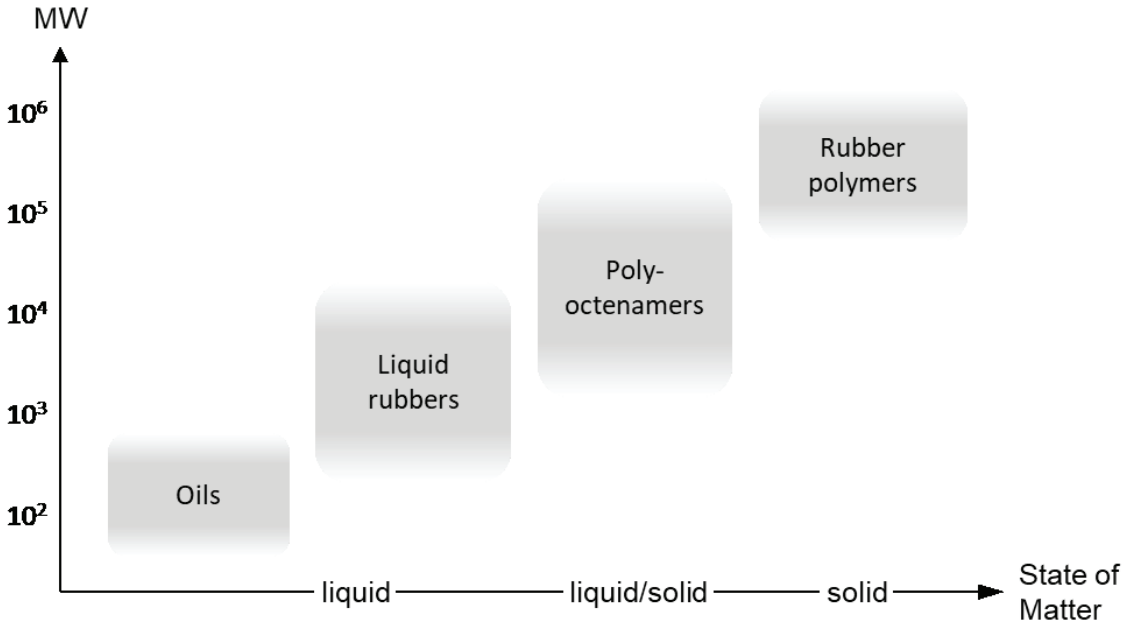


Figure 1 – Categorizing poly-octenamers by molecular weight (MW)

Due to its versatile nature in rubber processing, it is difficult to categorize TOR in the sense of additive by function: it shares features of a plasticizer, green strength enhancer, anti-tack agent, compatibilitizer, and others. Therefore, trans-polyoctenamers should be considered as a class of its own.

By looking at the molecular weight, trans-polyoctenamer is in the range of 140.000 g/mol and can be understood as a material between liquid rubbers and "real" rubbers (**Figure 1**). In fact, TOR shares the best of two worlds by providing processing benefits like liquid rubbers and giving performance like a specialty rubber. The thermoplastic properties of TOR provide additional advantages, like being an easy to dose pellet at room temperature or showing a fast recrystallization what helps to keep green compounds stable in shape, reducing tack, and improving the storage stability of rubber blends.

This full package of properties is valued today in almost all application fields of rubber like tires, hoses, profiles, belts, molded products, linings, calandered articles, sports goods, medical products, foams, and many others. The widespread use is underlined by the growing number of scientific and patent publications about trans-polyoctenamer (**Figure 2**), indicating that this material continuously undergoes a global application innovation process - even beyond rubber applications.

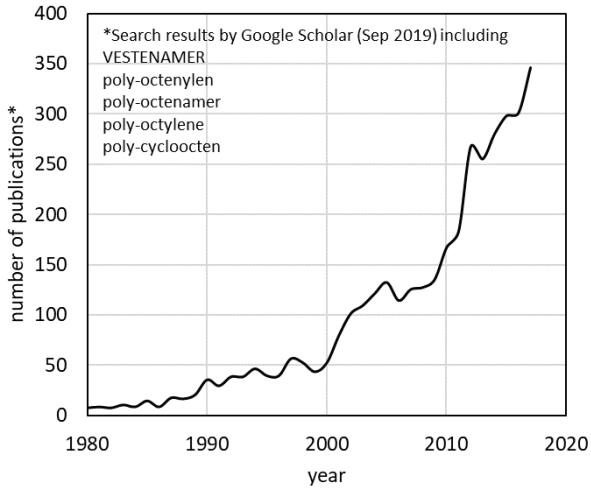


Figure 2 – Bibliometry of poly-octenamers in scientific and patent literature

CHALLENGES IN RECYCLING RUBBER

An appealing application on the rise is the combination of TOR with recycling rubber powders. Although first publication on this use have been published by Diedrich and Burns already 20 years ago,[13] the meaning of recycling rubber has nowadays gained much more importance.

One reason is that end-of-life tires are more and more recognized as a serious global waste problem, but also as raw material of ubiquitous availability – today the global amount of recovered tires is estimated 17.2 million metric tons.[14] The trend of how to use tire derived materials points clearly in the direction of material recovery (e.g. ground tire rubber) instead of energy recovery (e.g. burning in cement kilns). In Europe, the material recovery has grown from a one-digit minority share towards the dominating valorization route over the last 25 years.[15] In 2016, the amount of end-of-life tires that undergoes material recycling to ground tire rubber (GTR) has reached 1.424 metric kilotons, what states more than one third of the used tire arising in the European Union.[16]

Some typical applications of GTR and recycling rubber powders are rubber mats, molded goods, polymer component in virgin rubber compounds, infill for sports fields, rubber-modified asphalt, fillers for paints or coatings, and various other applications. Since recycling rubber is offered at much lower prices compared to virgin polymer materials, it can often significantly improve raw material costs of manufactured products.

Nevertheless, there are some common problems in the use of recycling rubber materials that limit its extended use in many cases. Recycling rubber is often difficult to process – increased viscosity, stickiness, and swelling by hydrocarbons are some examples. Moreover, a serious loss of mechanical properties limits the use of ground tire rubber as component in virgin rubber materials or thermoplastics. Ramarad et al. gives a comprehensive overview about typical challenges in polymer blends.[17] In general, we can summarize three major factors that determine ease of processing and performance of ground tire rubber (GTR) in applications:

1) Source of GTR
2) Particle size & morphology
3) Surface treatment

The source of GTR determines the base polymer content of the recycling material, e.g. whether it is from truck tire tread (high natural rubber content), passenger car tires (higher synthetic rubber content), or production scrap from EPDM products or other rubber types. For example, in rubber-modified asphalt, the choice of rubber has influence on the diffusion kinetics of bitumen – truck tires reach their swelling equilibrium state faster and can absorb more bitumen than car tires do.[18] This might be an advantage in application.

The particle size has also significant influence on product performance. In the above mentioned case of rubber-modified asphalt, smaller particle sizes improve storage stability[19] and reduce equilibrium swelling time even further.[18] When blending GTR into virgin rubber compounds, smaller particles typically result in better mechanical properties.[17] Moreover, the different grinding methods like ambient grinding, cryogenic grinding, or water jetting influence the particle morphology and result in different surface areas.

Finally, the surface modification of ground tire rubber can improve processing and product performance to a large extend. It can help to reduce processing problems like stickiness, raised viscosity, or better compatibility and interfacial bonding to matrix materials - whether it is about bitumen, virgin rubber, or thermoplastic materials. With regards to bonding, chemical cross-linking has been demonstrated to improve mechanical properties.[16] There are many ways to address the different challenges, e.g. using plasticizers to improve processing, or using chemical

treatments to improve compatibility. TOR plays an outstanding role here, since it fulfills all aspects, namely being a processing aid, improving performance, and being cross-linkable.

MODE OF ACTION

In general, TOR forms dispersed phases in rubber polymers, as shown by DSC measurements and microscopic analysis.[20] The fine-dispersed TOR phases provide a wetting effect, resulting in less shear forces, and hence easier mixing and processing of the rubber compound. In binary rubber blends, addition of TOR forms a third phase at the interphase. This intermediate layer compatibilitizes the rubber domains by reducing the interfacial tension between the two rubber components. Furthermore, the recombination of domains (coalescence) is inhibited by the TOR layer. This finally results in better dispersed blends and mechanical properties, even for practical immiscible combinations like EPDM/NBR.[21]

The ability to compatibilitize rubbers is a good pre-condition for application in recycling rubber powders. Materials like ground tire rubber typically comprise a wide spectrum of rubber polymer types and compositions, depending on their source and sorting. For example, passenger car tires dominate in synthetic rubber polymer content, whereas truck tire treads typically have more natural rubber content.

Adding TOR to recycling rubber crumbs or powders results in a similar wetting effect like in virgin rubber compounds. The difference is the "domain" sizes that are limited by the sizes of the already vulcanized recycling rubber particles. At temperatures above the melting point, TOR forms a surface layer on top of the particles. Although the coating process has been described,[13,22] few information on the surface coating itself is available. To close this knowledge gap, we conducted scanning electron microscopic (SEM) and transmission electron microscopy studies (TEM) to prove and investigate the quality and morphology of the assumed TOR coating layer.

Samples were prepared with internal laboratory mixer by mixing cryogenic milled GTR of 200µm size with 4.5 wt% TOR for 7 min. 10 randomly selected particles were taken from the prepared samples and analyzed by SEM, confirming successful coating for 9 of the 10 samples. **Figure 3** shows an uncoated GTR particle with rough surface structure, compared to a TOR-coated particle covered by a smooth surface. This visually confirms the wetting effect of TOR as well as the good compatibility and affinity to the recycling rubber particle surface.

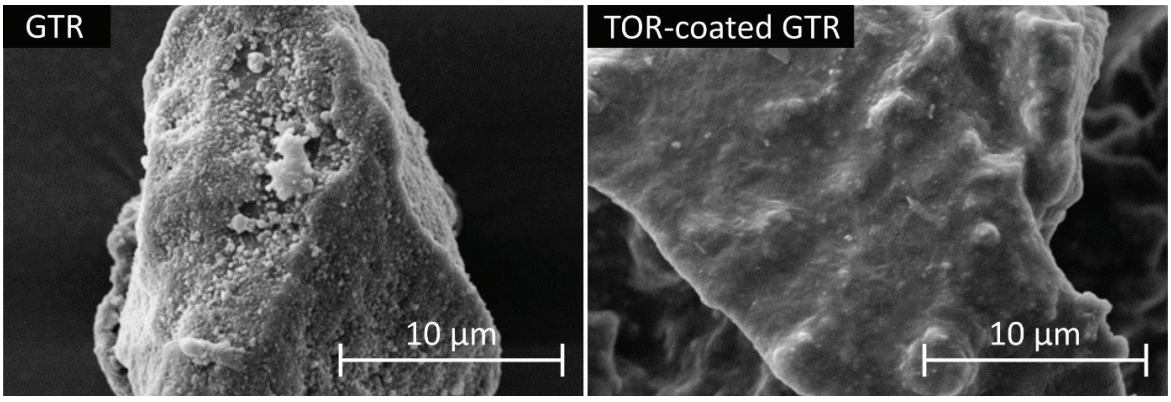


Figure 3 – SEM pictures of GTR particle (left-hand) and coating layer of TOR (right-hand)

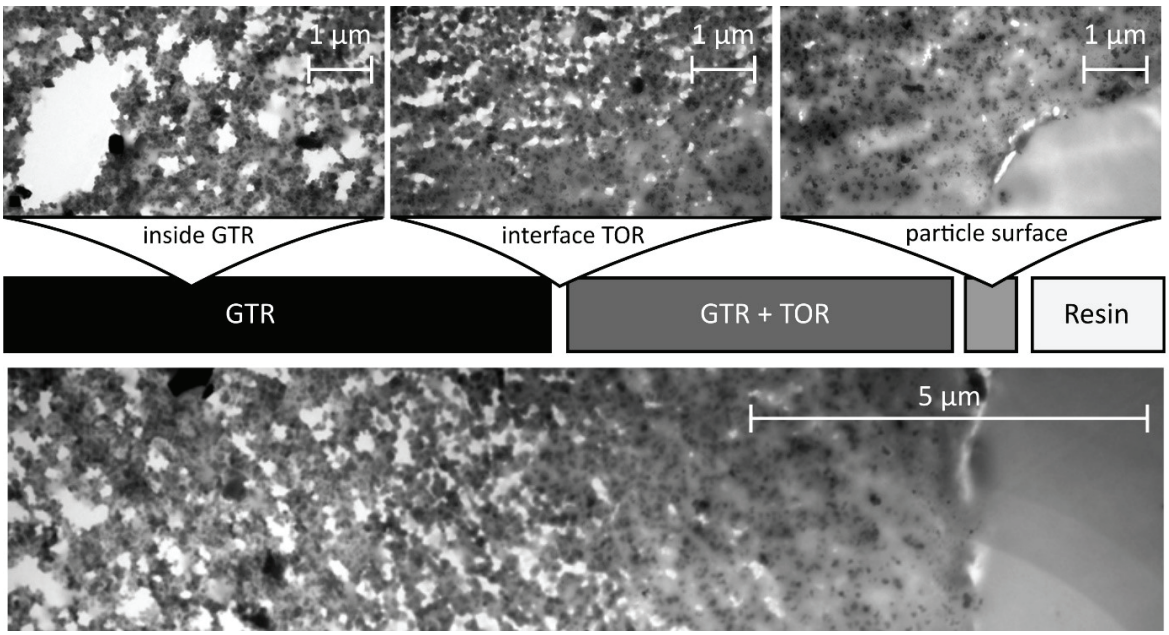


Figure 4 - TEM pictures of thin-film cuts of TOR-coated GTR particle

An even more detailed insight is revealed by the transmission electron microscopy of samples that were prepared by thin-film cuts. **Figure 4** shows the cross-section of a TOR-coated GTR particle, where the different zones of the GTR particle, TOR layer, and sample matrix can be identified. The TOR coating layer thickness can be estimated around 3-5 µm. Whereas the outer boundary of the surface layer is clearly visible, the inside of the particle shows a blurred transition from the TOR layer to the inside of the GTR particle. This indicates a diffusion and interpenetration of TOR into the surface of the GTR particle. This is in line with expectations from the solubility point of view - TOR shares similar chemical characteristics like common rubber polymers, and hence shows good compatibility as expressed by their solubility parameters.[20] Moreover, the concept of interpenetrating layers has already been described by Wenig et al. for blends of TOR with thermoplastics.[23,24]

The evidence for a good surface coating of GTR by TOR explains the well-described benefits in processing. TOR "masks" the GTR surface and thus prevents difficulties like higher stickiness and viscosity. It can also be assumed that the TOR layer influences diffusion kinetics, when it comes to migration processes between GTR and the embedding matrix. Reports about reduced emissions of GTR by TOR in asphalt applications[25] give some indications for that.

The performance improvements observed can also be explained by the TOR-coating layer. Since TOR is unsaturated and can be cross-linked like rubber, it offers a reactive surface towards the outside of the particle for compatibilization and/or cross-linking and can further cross-link inside the GTR particle along the interpenetrating layer. FTIR studies on the surface of TOR-coated GTR in bitumen application have shown that TOR undergoes chemical reaction at processing.[26] Since all curing chemical additives and accelerators are already present in the GTR particle (and furthermore undergo migration processes) this can be expected. Improved performance by adding additional sulfur has been reported.[27,28]

From the gained insights by electron microscopic analysis, as well as the literature review shown above, a mode of action for surface modification of GTR by trans-polyoctenamer can be concluded as depicted in **Figure 5**.

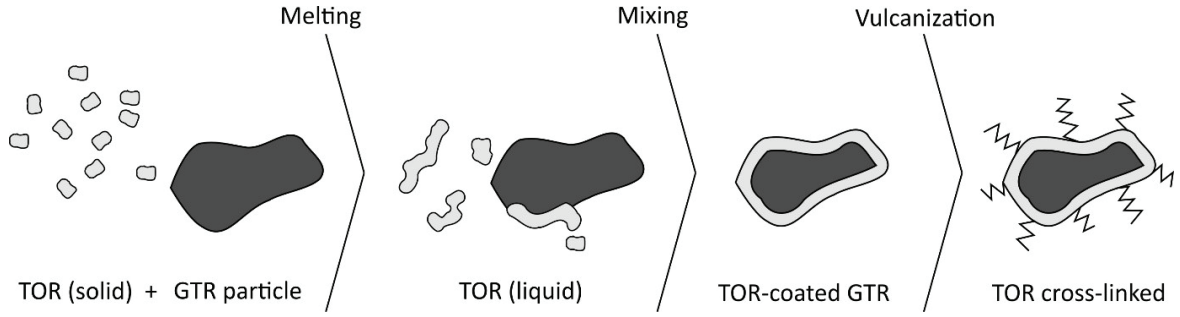


Figure 5 – Mode of action for TOR with ground tire rubber

TOR COATING PROCESS

For a proper function of the "TOR effects", a good coating of the rubber particles is an important pre-requisite. From our experience there are different ways on how to achieve this, depending on the available mixing equipment.

If internal mixer is available, like in rubber compounding facilities, TOR can simply be added together with GTR to get the desired result.[13] In laboratory procedures, a pre-heating of TOR can improve results and lower the mixing time. The samples shown in **Figure 4** and **5** were prepared with a mixing time of 7 min, without addition of oil.

If internal mixer is not available, powder blenders can also be used. This states a less capital-intensive mixing option. Since this option provides less intensive mixing compared to internal or Banbury type mixers, the coating process of the particles can be facilitated by employing an oil solution of TOR. A common formulation is 20 wt% of TOR dissolved at elevated temperatures (100-120°C) in a suitable oil, like paraffinic oil. Rubber process oils like TDAE work as well. Different solubilities of TOR have been observed by us in various oil types (**Table 2**).

A further option is extruding equipment used for continuous mixing of GTR with TOR. If curing-chemicals are added, recycling rubber compounds can be produced that are ready for press- or injection-molding process. This has proved to be an efficient process for large-scale production of rubber mats from recycling rubber powders.

	Naphthenic black oil	**TDAE process oil**	**Paraffinic process oil**	**White oil**
	Nytex 4700	Vivatec 500	Sunpar 2280	Infrasolv LC1
10 wt% TOR	yes	yes	yes	yes
20 wt% TOR	yes	yes	yes	yes
30 wt% TOR	yes	partially	no	yes

Table 2 – Solubility of TOR in different oils at 100°C

TOR AS BINDER SYSTEM FOR MOLDED PRODUCTS FROM GTR

The dominating binder system for molded products from GTR is polyurethane (PU), what is easy to process, and needs no elevated vulcanization temperatures for production of molded goods. TOR is an alternative binder option to make new molded products from GTR but needs vulcanization temperatures in press-curing comparable to production of virgin rubber products. Although the energy consumption might be higher than in PU processing, TOR can be an attractive option due to the good mechanical properties of the vulcanizates and their superior weathering resistance.[29] Considering the lower dosage needed for TOR compared to PU, it can also economically compete by taking the total costs of formulation and processing into account. The effective amount of TOR needed is 3 parts per hundred parts of GTR. A standard formulation for GTR compound with TOR binder, and the range of the respective physical properties for 20-40 mesh size GTRs of various sources is shown in **Table 3**.

It can also be assumed that the chemical resistance of TOR-bound GTR articles is superior in many points compared to PU because it shares characteristics of polyolefinic materials and has a non-branched chemical structure. This is desirable for products that undergo chemical stress like animal bedding mats that are exposed to excrements, and hence must withstand acid environment. Therefore, TOR improves price performance ratio of such products by enhancing their lifetime.

Recyclability becomes more and more important in the long-term transformation of our society that pushes towards a circular economy. In this respect we see some further general advantage of using TOR compared to other binder systems. Since TOR is a rubber-material itself, “rubber stays rubber” and does not become a composite product like PU/GTR. This could simplify a further recycling step of GTR products and might help to give tires not only a second life, but even a third live: in rubber products or up-cycling to other applications like rubber-modified bitumen and asphalt. Nevertheless, studies are needed to show the practical feasibility of such a third life concept.

Material	phr	Properties	Unit	Value
GTR (20-40 mesh, PCR tire)	100	Press curing	min	20
TOR / Oil	3 / 12			
ZnO	0.1	Hardness	Shore A	64-74
Stearic acid	0.5	Tensile strength	MPa	4.5-8.5
Sulfur	0.8	Elongation at break	%	150-300
CBS	0.8	Modulus 100 %	MPa	2.0–3.0
TMTD	0.2	Rebound resilience	%	50-60

Table 3 - Standard recipe for GTR products with TOR and properties of the vulcanizate

TOR-COATED GTR IN VIRGIN RUBBER

The cost of GTR can go down to one order of magnitude lower than virgin rubber materials, depending on grinding method and size. This makes it an attractive raw material - not only from the ecological, but also from the economic point of view. On the other side, serious processing and performance problems arise when production scrap or ground tire rubber materials are introduced into virgin rubber compounds. The reason for this is due to migration processes between GTR and rubber matrix as well as insufficient incorporation and bonding of the embedded GTR particles. The problems typically scale with the percentage of recycling rubber compounded into the virgin formulations.[17] Hence, its applicability is strongly limited, especially in safety critical applications like tires.

Technologies that enable the use of production scrap or ground tire rubber materials are key to extend the use of these recycling materials. TOR can narrow, or even close, many technical gaps that are often prohibitive factors for using GTR in virgin rubber compounds. This has been demonstrated by trials with some test SBR and NR compounds that were filled by 20 and 40 phr GTR. The reviewed formulations[29] are summarized in **Table 4**.

Materials	**SBR**	**SBR-GTR**		**SBR-GTR-TOR**		**NR**	**NR-GTR**		**NR-GTR-TOR**	
SBR 1500	100	100	100	100	100	-	-	-	-	-
NR	-	-	-	-	-	100	100	100	100	100
Carbon black N33	60	60	60	60	60	60	60	60	60	60
GTR	-	20	40	-	-	-	20	40	-	-
GTR coated (TOR)	-	-	-	20 (0.6)	40 (1.2)	-	-	-	20 (0.6)	40 (1.2)
Oil, aromatic	10	10	10	10	10	10	10	10	10	10
Antiageing package	5	5	5	5	5	5	5	5	5	5
ZnO	5	5	5	5	5	5	5	5	5	5
Stearic acid	1	1	1	1	1	1	1	1	1	1
Sulfur	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
CBS	1	1	1	1	1	1	1	1	1	1
CTP	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 4 – Test formulations of SBR and NR

A typical challenge is the viscosity increase of the green compound that arises when GTR is added in larger amounts. The use of TOR-coated GTR shows improvements over untreated GTR as summarized in **Figure 6**. This is a result of the TOR/oil solution coating that reduces Mooney viscosity very close to the level of the reference compound. Further data reveals improved tensile strength where TOR improves by around 1 Mpa. The test data on compression set shows an impressive effect that illustrates the cross-linking function of TOR between GTR and virgin polymer matrix quite well. As visible from the data in **Figure 7**, the loss in compression set by GTR incorporation can be completely prevented by applying the TOR-coating. This can be of great advantage for applications in seals, gaskets, or dampers, where compression set is an important property.

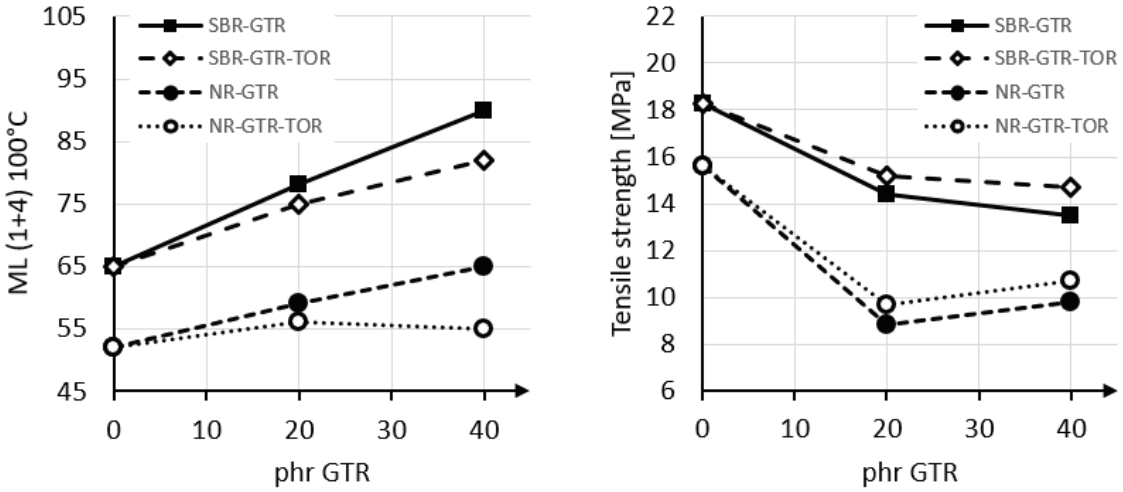


Figure 6 - Influence of TOR-coating on Mooney viscosity (left-hand) and tensile strength (right-hand)

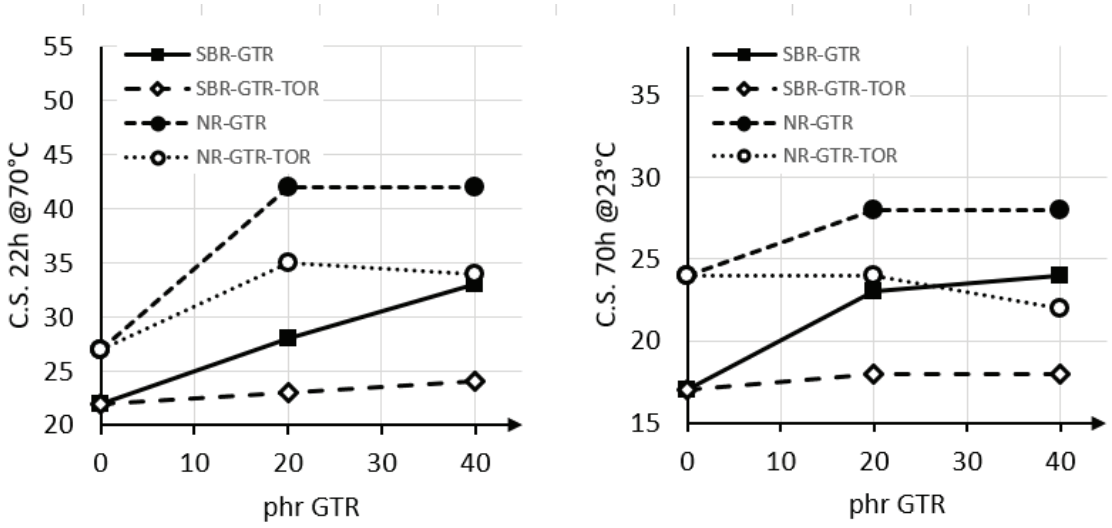


Figure 7 - Influence of TOR-coating on compression set

RUBBER MODIFICATION OF BITUMEN AND ASPHALT

Trans-polyoctenamer has a track-record of more than 25 years as a processing additive in the bitumen and asphalt industry. Recycling rubber acts as a polymer modifier that improves binder properties of bitumen, and hence of the modified asphalt.[30] The environmental benefits of using recycling rubber is an additional argument from the perspective of sustainability and circular economy discussions.[31–33]

Although the benefits of rubber in road construction are known for a long time, it is faced with practical problems in processing like stickiness, storage problems, or emission. Moreover, lack of knowledge about best practices in working with rubber has been a hurdle that inhibited wider adoption of rubber-modification in asphalt in the past. For example, swelling times[18] and working temperatures[34,35] are critical issues to take care of in rubber-modification.

Situation has changed today as rubber-modification moves towards more acceptance and has even found entry into national strategies.[36] TOR is part of this process, since it helps to overcome the critical challenges in the practical application of rubber in road construction. The benefits of reduced stickiness, improved rutting resistance, and reduced cracks have been confirmed by many researchers all over the world.[26,27,37–47] TOR moreover helps to improve storage stability and pumpability of rubberized asphalt,[26,48] what is a key challenge in wet process. Positive effects on thermal stability have also been reported recently.[25,44]

From road construction perspective, rubber is a temperature-sensitive raw material, what means that working at lower temperature is favorable in terms of emission. On the other side, low temperatures lead to higher viscosities, what can be a problem when bitumen is processed at too low temperatures. During paving the TOR-effect brings significant benefit, since it reduces the compaction resistance of rubber-modified asphalt. This opens a wider temperature window for processing and therefore gives more process safety. Influence of TOR on lower compaction resistance is shown in **Figure 8**. The effect can also be explained by the coating mode of action (**Figure 5**), since the swollen and sticky GTR surface is coated by TOR what reduces the effective stickiness of the rubber particles. This is also valued at un-loading of trucks, where asphalt residues on the machinery often makes

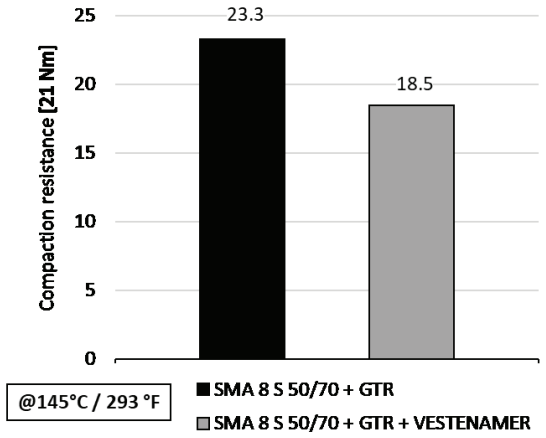


Figure 8 - Compaction resistance reduction of rubber-modified asphalt by TOR

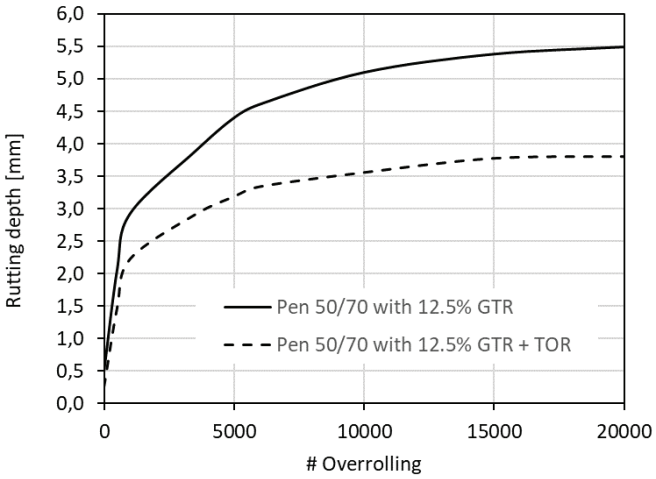


Figure 9 - Rutting depth results by Hamburg-tests of rubber-modified asphalt by GTR and GTR/TOR

tedious cleaning efforts necessary. Beside the easier processing, TOR has also positive impact on the performance of asphalt pavements. One example is the improved rutting resistance. As visible from the Hamburg-tests in **Figure 9**, rutting depth is reduced using TOR compared to the rubberized asphalt mixture without TOR. In this laboratory test method, a test wheel rolls over the prepared asphalt sample for several thousand times.

Together with the other benefits, like improved long-term aging, GTR and TOR can therefore significantly extend the lifetime of pavements. Long-term experiences by well-documented paving projects, e.g. laying for more than 11 years now, prove the laboratory results by showing a road surface in perfect state, without any rutting or cracks (**Figure 10**).



Figure 10 - Rubber-modified industrial area in Germany after 11 years of heavy traffic load

In asphalt application, the use of reclaimed asphalt pavement (RAP) is a further leverage towards more sustainability in road construction. The use of rubber-modification is a perfect fit to improve the aged binders in reclaimed asphalt. From our recent studies that will be published soon, we see that use of 50% RAP in top layer is possible without compromising standards and expectations of modern road construction.

SUMMARY

In summary, TOR is a unique tool to overcome many challenges that arise in the use of GTR, hence pushing boundaries of what is possible with the cost-efficient, sustainable, and ubiquitous available raw material ground tire rubber.

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