Australia's National
Science Agency

Exploring global influences on the tyre industry: Chemicals of concern, microplastics and design

LITERATURE REVIEW

Final report prepared for
Tyre Stewardship Australia

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Contents

List of Tables

List of Abbreviations

Abbreviation	Definition
6PPD	N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine
7PPD	N-(1,4-dimethylpentyl)-N'-phenyl-p-phenylenediamine
ADCA	Azodicarbonamide
AICIS	Australian Industrial Chemicals Introduction Scheme
APVMA	Australian Pesticides And Veterinary Medicines Authority
ARN	Assessment Of Regulatory Needs
CAA	Clean Air Act
CBAM	Carbon Border Adjustment Mechanism
CCPD	N-cyclohexyl-n'-phenyl-p-phenylenediamine
CenTiRe	Center For Tire Research
CERTH	Centre For Research And Technology Hellas
CMP	Chemicals Management Plan
CNRS	Centre National De La Recherche Scientifique
CNTs	Carbon Nanotubes
CPERI	Chemical Process And Energy Resources Institute
CRADA	Cooperative Research And Development Agreement
CSIC	Consejo Superior De Investigaciones Científicas
CSCL	Chemical Substances Control Law
CSRD	Corporate Sustainability Reporting Directive
CWA	Clean Water Act
DoE	Department Of Energy
DPG	Diphenyl Guanidine
DTSC	Department Of Toxic Substances Control
ECHA	European Chemicals Agency
Enviro	Enviro Systems
EOL	End-Of-Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
ESG	Environmental, Social, And Governance
ESPR	Ecodesign For Sustainable Products Regulation
ETRMA	European Tyre And Rubber Manufacturers' Association

EU	European Union
EUDR	European Anti-Deforestation Regulation
EU REACH	European Union Registration, Evaluation, Authorisation And Restriction Of Chemicals
EURMI	European Raw Material Initiative
EV	Electric Vehicle
GADSL	Global Automotive Declarable Substance List
GASG	Global Automotive Stakeholders Group
GIZ	Gesellschaft Für Internationale Zusammenarbeit
GPSNR	Global Platform For Sustainable Natural Rubber
HCBD	Hexachloro-1,3-butadiene
HSNO	Hazardous Substances And New Organisms
IMDS	International Material Data System
IRSG	International Rubber Study Group
LIFE	Losartan Intervention For Endpoint
LLC	Limited Liability Company
MMM	Methoxymethyl Melamines
MRD	Molecular Rebar Design, LLC
NESHAP	National Emission Standards For Hazardous Air Pollutants
NICNAS	National Industrial Chemicals Notification And Assessment Scheme
NSF	National Science Foundation
NSNR	New Substances Notification Regulations
NZ	New Zealand
OEM	Original Equipment Manufacturer
OSPAR	Oslo And Paris
PAHs	Polycyclic Aromatic Hydrocarbons
PET	Polyethylene Terephthalate
PPDs	Phenylene Diamines
PREPOD	Propanone, Reaction Products With Diphenylamine
PVC	Polyvinyl Chloride
REACH	Registration, Evaluation, Authorisation And Restriction Of Chemicals
RHA	Rice Husk Ash
RMOA	Risk Management Option Analysis
SBIR	Small Business Innovation Research

SBR	Styrene Butadiene Rubber
SMEs	Small And Medium-Sized Enterprise
SMM	Sustainable Materials Management
SVHC	Substances Of Very High Concern
TIP	Tyre Industry Project
TRWP	Tyre And Road Wear Particles
TSA	Tyre Stewardship Australia
TSCA	Toxic Substances Control Act
UK	United Kingdom
UK REACH	United Kingdom Registration, Evaluation, Authorisation And Restriction Of Chemicals
USA	United States Of America
USDA-ARS	US Department Of Agriculture-Agricultural Research Service
US EPA	United States Environmental Protection Agency
USTMA	United States Tyre Manufacturers Association

Executive Summary

There is growing concern regarding contaminants originating from tyres that have prompted responses from tyre manufacturers, researchers, and regulators, leading to new research initiatives and regulations globally. As Australia considers end-of-life (EOL) tyre management and seeks to increase and diversify the uses for recycled tyres, a comprehensive understanding of the global context in tyre design, development, regulation, and management becomes crucial. This study undertook a literature review to address key research questions raised by Tyre Stewardship Australia (TSA):

1. What global regulations and policies are being introduced to mandate changes in tyre composition within the tyre industry?
2. How are tyre industry players addressing and publicly communicating changes in tyre designs to mitigate tyre wear and release of chemicals of concern?
3. What ongoing research initiatives and coordinated efforts are driving changes in tyre design globally?
4. While the United States of America (USA) and the European Union (EU) are actively engaging in regulatory measures to eliminate chemicals of concern, what is the stance of the United Kingdom (UK), Canada, New Zealand (NZ), and Asia? Are these regions more progressive than Australia, or are they adopting a more passive approach?

This study focuses on emerging "chemicals of concern" or chemicals that have been recently detected in the environment and are not yet fully understood in terms of their potential impacts on human health and ecosystems.[1] For example, the quinone derivative of a common tyre additive N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), known as 6PPD-Q, has renewed scientific interest in chemicals in tyres due to its widespread presence in road runoff and toxicity to a range of organisms.[2,3,4] Additionally, concerns about microplastics from tyre wear are also growing, with recent estimates suggesting that tyre wear contributes 5–10% of global microplastic emissions.[5]

The review begins with an examination of various regulations and policies to establish the legal framework governing tyre design and to set a baseline for further discussion. This is followed by an exploration of tyre industry efforts to bridge regulations with practical implementation, addressing how regulations impact the industry efforts. Next, ongoing research initiatives and coordinated efforts are highlighted to showcase other advancements occurring outside the tyre industry. Finally, insights into global regulatory measures are discussed to inform Australia's approach to managing chemicals of concern.

Each section provides a summary of the current state of knowledge based on publicly-accessible literature, rather than a comprehensive academic review of the literature. The summaries could provide insights that may benefit Australia through accurate forecasting of materials in the EOL tyre stream, thus improving planning and resource allocation. It can help in optimisation of recycling processes and technologies for future tyre compositions, enhancing recycling rates and product quality.

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[1] The term "chemicals of concern" is often used in regulatory context to identify chemicals that need further study or control.

[2] https://www.science.org/doi/10.1126/science.abd6951

[3] https://pubs.acs.org/doi/10.1021/acs.estlett.2c00050

[4] https://www.sciencedirect.com/science/article/pii/S0160412024002630

[5] https://www.mdpi.com/1660-4601/14/10/1265

Anticipating design changes can also ensure products developed using this new EOL tyre waste stream comply with future regulations. Overall, understanding tyre design trends can help future-proof strategies, and ensure long-term sustainability for industries such as tyre recycling and automotive manufacturing.

KEY FINDINGS

The tyre industry is being influenced by significant regulatory changes worldwide, aimed at reducing environmental impacts and enhancing safety. These regulations focus on various aspects, including the materials used in tyre production, the reduction of hazardous substances, and the promotion of sustainable practices. Key regulatory bodies such as the European Chemicals Agency (ECHA), the US Environmental Protection Agency (EPA), and international standards organisations are at the forefront of these efforts, implementing stringent policies and regulations to promote the development of eco-friendly tyres that are protective of human health and the environment.

Both the EU and US are addressing chemicals of concern in tyres, the value of natural rubber, alongside concerns about tyre particle emissions, through multiple regulations and policies. The EU is more proactive in their approach to managing chemicals of concern than the US. For instance, the EU is already evaluating the risks of 6PPD, the precursor to the toxic chemical 6PPD-Q found in the environment, alongside structurally similar amino-substituted diarylamines under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation. Additionally, the EU is advancing the Euro 7 emission standards to reduce particle emissions, including microplastics in materials. Sustainability and circular economy approaches are also emphasised in the EU, with various policies and regulations (e.g., Corporate Sustainability Reporting Directive (CSRD); Carbon Border Adjustment Mechanism (CBAM); Extended Producer Responsibility (EPR); Ecodesign for Sustainable Products Regulation). In contrast, the US has a more reactive approach to managing chemicals of concern. For example, their response to concerns with 6PPD-Q has been dominated by controlling pollution from tyre wear entering waterways and proposing bans on chemicals of emerging concern (e.g., tyres containing 6PPD and Zn are listed as priority products in California). Unlike the EU, which is reviewing a broader group of chemicals including potential 6PPD substitutes (amino-substituted diarylamines) that could have similar effects, the initial assessments in the US only focus on 6PPD. In addition to chemicals of emerging concern, sustainability is not as strongly emphasised in US policies.

Other chemicals of interest that are associated with tyres have been flagged by both REACH and the US Toxic Substances Control Act (TSCA) as of concern but are currently not regulated. Whilst natural rubber is recognised as a critical resource in the EU and USA, policies like the Raw Material Initiative (EURMI) and the Anti-Deforestation Regulation (EUDR) are more firmly established in the EU than in the US. Overall, the regulations and policies identified for chemicals of concern promote the following changes in tyres:

(1) promote alternative and more sustainable rubber sources;

(2) increased incorporation of recycled materials and product circularity;

(3) tyres with reduced wear to limit particle emissions;

(4) substitution of 6PPD and Zn in tyres with no loss of performance or safety; and

(5) exploration of alternatives for compounds like benzothiazoles, 1,3-diphenyl guanidine (DPG), methoxymethyl melamines (MMM) in the US; and amino-substituted diarylamines, 1-octanethiol, aniline, and benzothiazoles in Europe.

From the tyre industry standpoint, many of their endeavours are linked to meeting established regulations and criteria, such as the CSRD, CBAM and EPR, all designed to decrease environmental harm and foster sustainability.

Additionally, schemes like the Euro 7 emission standards, the EUDR, and the EURMI specifically address reducing emissions, preventing deforestation, and managing resources (i.e., rubber). In general, manufacturers tend to emphasise initiatives to meet sustainability objectives and key performance needs such as safety (e.g., wet grip) and fuel efficiency (e.g., rolling resistance), while efforts to mitigate tyre wear and address chemicals of concern are secondary.

For instance, Michelin's e.Primacy tyres, and Pirelli's P ZERO E tyre, are all marketed primarily for their use of less fossil fuels and more sustainable rubber sources and less so for their ability to reduce particle emissions. Efforts to address chemicals of concern that are highlighted in global regulations, receive less attention on individual manufacturer websites and are featured in large-scale collaborations led by associations or government bodies. For example, the search for 6PPD alternatives is driven by potential bans in the US with initiatives led by the US Tyre Manufacturers Association (USTMA) and US Department of Agriculture-Agricultural Research Service (USDA-ARS). Similar activities in Europe (not led by tyre manufacturers) focus more on tyre emissions, recyclability, and sustainability, such as the Tyre Industry Project (TIP), The European Tyre and Road Wear Platform, BlackCycle, and WhiteCycle, aligned with European regulations.

At the academic, industry, and consortium levels, research explores a broad range of potential innovations in tyre design and manufacturing. The majority of research, often involving industry partners, align with the focus areas identified in tyre manufacturers' initiatives with other research areas dictated by government interests. For instance, the US National Science Foundation (NSF) Center for Tyre Research (CenTiRe), established under NSF's Industry-University Cooperative Research Center's Program with around 21 affiliated member organisations, focuses on various fundamental research areas, with sustainability as a key theme which mirrors what tyre manufacturers communicate in their websites.

Replacements for traditional fillers, processing oils, and additives, such as accelerators and anti-degradants like 6PPD are also being actively explored, in addition to finding more sustainable natural rubber sources and reintegrating EOL materials back into new tyres. For example, Pirelli and Bridgestone have collaborations focused on the effective use of silica to reduce carbon black usage. Progress is also being made in developing innovations in tread designs, polymers, fillers, and nanomaterials, like self-healing materials based on graphene oxide and ground tyre rubber to enhance tyre lifespan and reduce wear. Concepts like "green tyres" and "bio-based tyres" are prominent in academic literature, involving renewable resource-based polymer materials, eco-friendly macromolecule modifications, and replacing harmful components. Techniques like finite element analysis are being used for simulations to predict and optimise properties like rolling resistance and durability to accelerate tyre development.

The replacement of chemicals of concern in tyres appears secondary in these initiatives, likely because global regulations regarding such chemicals in tyres are still evolving. These regulations tend to vary across different regions, with the EU and US having the most mature systems globally. The EU's centralised approach (REACH) prioritises chemical safety and innovation, harmonising regulations across member states. In the US, federal regulations (TSCA) provide a foundation, but state autonomy and the evolving ESG (Environmental, Social, and Governance) landscape exert considerable influence.

In the EU, the REACH regulation adopts a more proactive and precautionary approach in categorising and regulating chemicals of concern and setting data requirements, while US TSCA tends to have a more reactive risk-based approach to regulation, as seen with the 6PPD situation. New Zealand's strategy leans towards conservatism, prioritising risk management over elimination, although there seems to be an evolution in the regulation of chemicals. Asian nations, especially Japan and China, display a growing level of proactivity, while India's regulatory landscape is still in the development phase. Political structures significantly influence regulatory advancement in these Asian regions. In comparison, Australia generally adopts a balanced, science-based approach to regulating chemicals of concern, often leveraging international data and standards. This approach tends to be more passive-reactive.

KEY INSIGHTS

Tyre design changes

The changes in tyre design can be categorised into structural/physical and compositional/chemical. Structural changes include tread designs, size, thickness, and reinforcements, whilst compositional changes involve rubber type, fillers, and additives like polymers, silica, carbon black, nanomaterials, and oils. Regulatory requirements are driving changes in tyres, such as replacing restricted chemicals like 6PPD, changing to more sustainable rubber sources, and designing tyres such that tyre abrasion rates are low. These changes may challenge existing recycling efforts, potentially complicating physical separation processes or impacting recycled product quality. For instance, tyres with enhanced durability due to engineering and reinforcements may require modifications to current handling systems for recycling compatibility. As manufacturers explore sustainable natural rubber sources, the EOL tyre market may see varying rubber compositions and qualities. Tyres using guayule, dandelion rubber, other bio-derived materials, soybean, or sunflower oils, or infused with nanomaterials may exhibit different properties than current EOL tyres. Such compositional shifts may necessitate reevaluating EOL tyre product pathways and the applicability of current recycling strategies.

Chemicals of concern

Regarding chemicals of concern, the current focus is on replacing 6PPD (precursor to toxic 6PPD-Q) and reducing tyre wear (source of microplastics). Consequently, future tyres in Australia might differ in composition depending on how manufacturers address these issues. For 6PPD, various alternatives are being explored, including 7PPD, IPPD, 77PPD, CCPD, and graphene. Asahi Kasei Corporation is taking a different approach by enhancing ozone resistance of rubber without similar chemical additives to reduce environmental risks. Molecular Rebar design with carbon nanotubes (CNTs) is being explored as another alternative despite recognised potential human health risks. Among these options, direct chemical replacement may be less disruptive and could be well-received by the community. The USTMA 6PPD consortium is an example of industry-led initiative to identify possible alternatives to 6PPD in big-name tyre brands. To reduce tyre wear, manufacturers employ optimised tread designs, reinforced structures (Kevlar, fibres), and additives such as carbon black and silica. While these approaches are common, the specifics, like tread design and silica used, can vary among manufacturers and may be subject to proprietary formulations leading to significant diversification in materials. Examples include tyres like ePrimacy, P-ZERO E, which will likely increase in the market as the popularity of electric/hybrid vehicles increases. From an EOL perspective, challenges may arise in managing EOL tyres due to structural and chemical changes in tyre design. Advanced techniques may be needed to separate fibres used to reinforce tyres from the rubber matrix, different grinding and devulcanisation techniques also need to be explored for silica-based tyres that are introduced to improve durability.

It is important to note that while the current focus of regulations is on 6PPD and tyre wear, there are other chemicals (e.g., benzothiazoles, DPG, and MMM) that are of potential concern and require assessment. Future regulations could prompt replacements or further changes in tyre design if research identifies significant risks to human health and the environment. This assessment and regulation is likely to again be driven by researchers and government bodies (just like 6PPD) and not initiated by manufacturers/companies.

Adapting recycling processes for future tyre designs

As many industries strive for greater sustainability and circularity, several programs and initiatives are investing in tyre recycling research and development.

Notable initiatives include the BlackCycle project and EVERTYRE initiative by Bridgestone, which aims to produce new tyres from EOL tyres; the Tyre Recycling Foundation, focused on recycling 100% of EOL tyres into circular, sustainable markets like rubber-modified asphalt; Enviro's pyrolysis-based technology for recovering high-quality carbon black; and Life Green Vulcan, which seeks to enhance tyre recycling through an environmentally friendly devulcanisation process.

While these programs could potentially help address current EOL tyres, it remains uncertain how these systems will adapt to potential changes in tyre design and manufacturing. Current recycling processes, such as pyrolysis or devulcanisation, may not be directly applicable to new materials and products. Questions arise, such as whether carbon black recovered multiple times from pyrolysis can maintain its quality; whether pyrolysis remains justifiable for tyres with increased silica content; if the same devulcanisation processes will apply to tyres produced with Molecular Rebar; and the viability of rubber-modified asphalt for different rubber types.

To achieve sustainable tyre manufacturing by 2050, integrating new designs, materials and chemicals into development of recycling processes is crucial. Whole-of-life considerations are necessary for new tyres to understand their fit in current EOL markets and potential impacts on human health and the environment.

Regulatory alignment

Aligning with international standards can offer valuable guidance for regulating of chemicals of concern in tyres, as these standards often influence decision-making in Australia. These global standards will need to be adapted to fit the Australian context, balancing international norms and local practicality. Data on chemicals of concern in tyres entering Australia, an understanding of relevant exposure pathways, and assessments of effects on local species are key pieces of information needed to ensure that international standards are relevant and applicable in the local context. It is important to also balance reactive and precautionary regulations to protect human health and the environment, while avoiding undue burdens on industry and maintaining practical feasibility and safety. This balanced approach should consider industry capabilities, economic impacts, and environmental and human health protection.

From an EOL perspective, it is important to evaluate these global regulations and collect Australian data when determining pathways for reuse/repurposing tyre products. Potential risks from chemicals other than 6PPD should be recognised and can help shape recycling processes and products to lessen their environmental impact, irrespective of regulatory outcomes. It is also important to consider the consequences of US restrictions/bans on 6PPD-containing tyres for Australia. These tyres could be redirected to regions with less stringent regulations, including Australia. On the other hand, if Australia imposes similar restrictions, the tyre industry might face higher costs, supply chain disruptions, and reduced competitiveness. However, these challenges must be weighed against the potential environmental and health benefits, and what could be managed.

In summary, staying informed about potential future developments in the tyre manufacturing, research, and regulations can lead to better decisions on recycling technologies and markets for incoming tyres. By implementing a strategy tailored to Australia's specific needs and aligned with international regulations, Australia can enhance its trade and collaboration with other countries, creating new opportunities for Australian recycled tyre products. Whilst aligning with the strictest global standards may prevent Australia from becoming a dumping ground for non-compliant products, it is crucial to assess the potential impact on the tyre industry. Finding the right balance between effectively managing risks and avoiding unnecessary burdens is essential. Collaboration among tyre manufacturers, regulatory agencies, researchers, and organisations like TSA is crucial for generating local data, strengthening future strategies and ensuring a circular economy for all used tyres.

1 Introduction

BACKGROUND

Over the past five years, there has been a growing focus within the scientific community on the environmental implications of tyres throughout their life cycle—from their use to their reuse and recycling stages.[6,7,8] Despite the limited discussions on tyres as potential sources of contaminants, their widespread use, reuse, and recycling suggest that tyres could significantly contribute to contaminants present in the environment. Notably, in the UK and the US, an annual release of 300,000 tonnes of tyre wear has been estimated. The particles generated by the friction between tyres and the road surface can be a significant source of various organic and inorganic contaminants (e.g., tyre and road wear particles, microplastics, additives) that can be potentially toxic to different environmental receptors. For example, the quinone derivative of a common tyre additive N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), known as 6PPD-Q, has renewed scientific interest on chemicals in tyres due to its widespread presence in road runoff and toxicity to a range of organisms.[9,10,11] Additionally, concerns about microplastics from tyre wear are also growing, with recent estimates suggesting that tyre wear contributes 5–10% of global microplastic emissions.[12]

In addition to tyres on vehicles, the repurposing and recycling of end-of-life (EOL) tyres for various applications may introduce another pathway for chemicals to enter the environment. For instance, rubber crumbs and granules from tyres have been used in asphalt and artificial turf applications. In general, while the reuse and recycling of materials are important to address the growing waste problem, the design and use of the products from recycled materials needs to consider the chemicals they contain to minimise environmental release and potential impacts on human health and the environment. Chemicals present in these recycled or reused materials could be released at different stages of their lifecycle, posing risks, especially if proper controls are not implemented or if there is limited information about their composition, making it difficult to assess impacts and develop effective mitigation strategies.

Indeed, concerns regarding contaminants originating from tyres have prompted both reactive and proactive responses from tyre manufacturers, researchers, and regulators. This has resulted in new research initiatives and global regulations aimed at managing current contamination issues and addressing the problem at its source by designing out contaminants.

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[6] https://doi.org/10.1016/j.scitotenv.2020.137823

[7] https://doi.org/10.1016/j.envpol.2022.119974

[8] https://doi.org/10.1016/j.jhazmat.2020.124998

[9] https://www.science.org/doi/10.1126/science.abd6951

[10] https://pubs.acs.org/doi/10.1021/acs.estlett.2c00050

[11] https://www.sciencedirect.com/science/article/pii/S0160412024002630

[12] https://www.mdpi.com/1660-4601/14/10/1265

PURPOSE

This report outlines the scope of a desktop study exploring global influences of contaminants of concern (chemicals and microplastics) on the tyre industry.

As Australia considers EOL tyre management, as well as increase and diversify the uses for recycled tyres, a comprehensive understanding of the global context in tyre design, development, regulation, and management becomes crucial.

This involves identifying best practices, recognizing emerging trends, and examining global regulatory frameworks and management practices. Ensuring that Australia's approach aligns with global standards and best practices in the tyre industry, as well as government and community values and expectations, is essential.

SCOPE AND METHODOLOGY

This study aims to address the key research questions raised by TSA regarding the global scenario of tyre design, development, and regulation, with a specific focus on chemicals of concern.

OVERVIEW OF KEY QUESTIONS

This report addresses the following key questions:

1. (SECTION 2) What global regulations and policies are being introduced to mandate changes in tyre composition within the tyre industry?
2. (SECTION 3) How are tyre industry players addressing and publicly communicating changes in tyre designs to mitigate tyre wear and chemicals of concern?
3. (SECTION 4) What ongoing research initiatives and coordinated efforts are driving changes in tyre design globally?
4. (SECTION 5) While the United States of America (US) and European Union (EU) are actively engaging in regulatory measures to eliminate chemicals of concern, what is the stance of United Kingdom (UK), Canada, New Zealand (NZ), and Asia? Are these regions more proactive than Australia, or are they adopting a more passive approach?

PROJECT OBJECTIVES

To answer these research questions, a review of literature was conducted to identify:

1. Global regulations and policies introduced to mandate changes in tyre composition within the tyre industry.
2. Industry initiatives and communications on changes in tyre designs to mitigate tyre wear and chemicals of concern.
3. Research initiatives and efforts driving changes in tyre design globally.
4. Current regulatory measures to eliminate chemicals of concern present in tyres worldwide, particularly approaches being taken in the UK, Canada, NZ, and Asia.

METHODOLOGY

Data was gathered from publicly-accessible sources, beginning with scientific databases and extending to grey literature searches. Given the short timeframe, the review aims to provide an overview of the current state of knowledge rather than an exhaustive examination of the literature.

PROJECT BENEFITS

Results from this review can gain significant benefits, including the following:

1. **Accurate Forecasting:** By understanding upcoming changes in tyre design, industries like TSA can accurately predict the types and quantities of materials that will enter the EOL tyre stream, facilitating better planning and resource allocation.
2. **Optimised Recycling Processes**: Knowing the future composition of tyres allows recyclers to adapt their processes and technologies to efficiently handle new materials, improving recycling rates and product quality.
3. **Regulatory Alignment**: Being informed about global trends will help align Australia's regulations on imported and new tires as well as sustainability standards. In addition, understanding upcoming design changes helps ensure that recycling processes and end products comply with future regulations.
4. **Future-Proofing**: Understanding tyre design trends helps future-proof strategies, ensuring long-term sustainability.

2 Global regulations and policies

WHAT GLOBAL REGULATIONS AND POLICIES ARE BEING INTRODUCED TO MANDATE CHANGES IN TYRE COMPOSITION WITHIN THE TYRE INDUSTRY?

The tyre industry is being influenced by significant regulatory changes worldwide, aimed at reducing environmental impacts and enhancing safety. These regulations focus on various aspects, including the materials used in tyre production, the reduction of hazardous substances, and the promotion of sustainable practices. Key regulatory bodies such as the European Chemicals Agency (ECHA), the US Environmental Protection Agency (EPA), and international standards organizations are at the forefront of these efforts, implementing stringent policies to ensure compliance and promote the development of eco-friendly tyres that are protective of human health and the environment.

Many of the regulations identified through the literature search primarily pertain to regulating raw materials/chemicals, with a secondary focus on emissions and dispersal, the latter reflecting increasing concerns regarding tyre wear, microplastics, and the release of hazardous chemicals. Most regulations have noted specific tyre-related chemicals of concern such as:

- polycyclic aromatic hydrocarbons (PAHs)
- chlorinated paraffins
- aniline
- 1-octanethiol
- benzothiazole
- 6PPD and 6PPD-Q
- 1,3-Diphenylguanidine (DPG)
- (methoxymethyl) melamines (MMM)
- octylphenol ethoxylates
- microplastics, i.e., synthetic polymer microparticles[13]

The pertinent regulations in the EU, US, and globally are discussed further below. Additionally, reviews covering some of these regulations are available in these sources.[14, 15]

REGULATIONS AND POTENTIAL CHANGES IN TYRE COMPOSITION

European Union (EU) setting

Among the regulations identified, the EU's REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation by the European Chemical's Agency (ECHA) is the most comprehensive.

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[13] According to Annex XVII to Regulation (EC) No 1907/2006, these are particles containing a solid polymer, to which additives or other substances may have been added, and where ≥ 1% w/w of particles have (i) all dimensions 0.1µm ≤ x ≤ 5mm, or (ii) a length of 0.3µm ≤ x ≤ 15mm and length to diameter ratio of >3.

[14] https://doi.org/10.1016/B978-0-12-811770-5.00004-2

[15] https://doi.org/10.1016/j.envpol.2022.119974

REACH addresses the production and use of all chemicals, and their potential impacts to both human health and environment. REACH prioritises chemical safety and innovation while harmonizing regulations across member states of the European Economic Area. REACH requires chemical companies to research the safety of their chemicals in products before those chemicals can be sold. REACH places greater responsibility on industry to manage the risks that chemicals may pose to human health and the environment. Over-all, REACH is considered to be proactive, adopting the precautionary principle. According to the 1992 Rio Declaration, this means, "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". This regulation has direct implications for mandating changes in tyre composition in the EU, where use of certain chemicals may be restricted if the risks (to humans and environment) are not adequately managed and hazardous ones can be replaced with safer alternatives. Hence, will influence raw materials and chemicals used in tyre manufacturing.

Regulations related to chemicals of concern

The EU REACH regulation currently restricts the use of PAHs, specific phthalates and synthetic polymer microparticles.[16,17] For tyres containing these chemicals at concentrations above 0.1%, suppliers are obliged to provide customers with information that will ensure the safe use of the tyre, including as a minimum, the name of the chemical. For the most part, the concentrations of these chemicals in tyres are already under this threshold.

Other rubber-related compounds that are currently regulated by ECHA are 6PPD,[18] 1-octanethiol,[19] aniline,[20] and benzothiazoles.[21] Though these compounds are not considered substances of very high concern (SVHC), and are not currently in the candidate list for phasing out, 6PPD, and aniline are on the list for assessment of regulatory needs (ARN). This indicates that concerns for these chemicals have been identified and authorities will need to assess the most appropriate way to address these concerns. For 6PPD, which is in the Oslo and Paris Convention's (OSPAR) List of Chemicals for Priority Action,[22] ECHA appears to be taking a proactive approach considering a wider list of related compounds. The ARN drafted list covers the group of amino-substituted diarylamines, which consists of 17 substances including 6PPD and 7PPD. Hence, compounds like 6PPD and 7PPD will also undergo assessment.[23] Whilst an ARN may not necessarily translate into a restriction or banning of compounds, it may provide *an early warning to the industry,* that replacements, substitutions, or alternatives compounds with comparable properties should be considered.

Similar to ECHA, the Netherlands government's recent risk management option analysis (RMOA) recommends enforcing an EU-wide restriction on 6PPD, with a proposal to combine 6PPD-related compounds such as 7PPD, 8PPD, IPPD, DPPD, EC 448-020-2, BENPAT 44PD and 77PD in a restriction dossier to overcome the problem of regrettable substitution with compounds from the same group.[24]

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[16] https://echa.europa.eu/substances-restricted-under-reach

[17] https://www.sciencedirect.com/science/article/pii/B9780128117705000042#s0035

[18] https://echa.europa.eu/substance-information/-/substanceinfo/100.011.222

[19] https://echa.europa.eu/substance-information/-/substanceinfo/100.003.562

[20] https://echa.europa.eu/substance-information/-/substanceinfo/100.000.491

[21] https://echa.europa.eu/sl/substance-information/-/substanceinfo/100.002.179

[22] https://www.ospar.org/work-areas/hasec/hazardous-substances/priority-action

[23] https://echa.europa.eu/documents/10162/014d13cf-fa14-e765-e444-b74a4381701f

[24] https://echa.europa.eu/documents/10162/12ea350b-982a-e78f-a412-dc24d3802033

Regulations related to raw materials

The use of natural rubber in tyres may also be changing with the EU Raw Material initiative (Document 52020DC0474)[25] published in 2017 which identified rubber as a critical resource. This initiative emphasizes the importance of securing a fair and sustainable supply of natural rubber for EU industries. Hence, changes in the rubber used in tyres may occur as the source of natural rubber diversifies (from Southeast Asia to Africa) and alternative rubber options (e.g., dandelion and guayule plants) are identified.

The European Green Deal's circular economy action plan[26] may also lead to a rise in the usage of recycled material in tyres, as it advocates for sustainable product design and encourages the utilisation of secondary raw materials rather than relying solely on virgin resources. The EU Anti-Deforestation Regulation (EUDR) EU 2023/1115 also supports the shift to more recycled content or alternative rubber sources as it seeks to combat deforestation and forest degradation, aiming to prevent EU products from contributing to these environmental challenges.[27]

In addition, regulations are promoting tyres with low carbon emissions. The Carbon Border Adjustment Mechanism (CBAM), set to be fully implemented in 2026, is the EU's tool to impose a fair price on the carbon emitted during the production of carbon-intensive goods entering the EU and encourage cleaner industrial production in non-EU countries.[28]

Recyclability and energy efficiency during production are also generic requirements for different product groups described in the Ecodesign Directive (2009/125/EC) and Ecodesign for Sustainable Products Regulation, [29] encouraging more environmentally sustainable and circular products.

Regulations related to tyre particle emissions

Tyres engineered for reduced wear are becoming more common as the Euro 7 emission standards encourage the production of tyres with low particulate emissions. This regulation was established to limit emissions from exhaust, brakes, and tyres from vehicles sold in the EU.

Other regulations

The Corporate Sustainability Reporting Directive (CSRD) will influence the manufacture of tyres by requiring companies to report on the environmental and societal impacts of their activities, as well as associated risks and opportunities. Through this sustainability reporting, companies are more likely to invest in tyre research and development that is well aligned with responsible manufacturing practices.

North American setting

In the US, the Toxic Substance Control Act (TSCA) is the nation’s primary chemical management law which allows the US EPA to regulate chemicals in commerce. The TSCA is managed by the US EPA’s Office of Pollution Prevention and Toxics. The US EPA evaluates potential risks from new and existing chemicals to address any unreasonable risks chemicals may have on human health and the environment. The Act provides the EPA with full range of options to address the risks of substances which includes labelling requirements, use restrictions, phase outs, or other appropriate actions for any chemical found to present an unreasonable risk.

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[25] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017DC0490

[26] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[27] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1115&qid=1687867231461

[28] https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

[29] https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

Hence, it may directly influence changes in tyre composition, and like REACH, US EPA can use this Act to impose restrictions or phase out of certain chemicals of concern. In addition to the TSCA, the Clean Air Act and the Clean Water Act are legislation that may influence the tyre industry by setting standards for emissions.

Regulations related to chemicals of concern

In the US, TSCA places restrictions on PAHs in materials and products, and there are proposals to extend these restrictions to other tyre-related compounds. A proposed rule for 6PPD would require manufacturers (including importers) to report chemical lists and published/unpublished health and safety studies to the EPA. Unlike the EU, where the focus is broader, the US assessment of 6PPD risks is limited to this compound and does not include the broader group of amino-substituted diarylamines.[30] To further protect the environment, the US EPA recently introduced (June 2024) non-regulatory and non-binding screening values (concentrations) based on short-term toxicity of 6PPD and 6PPD-Q to freshwater aquatic life that can be used to monitor waterways .[31] Research and investments are also being made to help treat and manage waters that contain these chemicals.[32]

Zinc (Zn) and 6PPD are set to be considered chemicals of concern in California as motor vehicle tyres have been proposed as priority products under the Safer Consumer Products Regulation. The California Department of Toxic Substances Control (DTSC) is considering restricting products containing Zn and 6PPD, and manufacturers are currently required to provide notification of their intent/confirmation to remove product/chemical or replace product-chemical.[33] Hence, the restriction and likely replacement of these chemicals in products appears to be imminent in California. The DTSC intends to designate motor vehicle tyres containing Zn as a Priority Product in a report published in November 2023.[34] The proposal indicates that there is a potential for people or the environment to be exposed to the Chemical of Concern in the Priority Product, potentially causing or contributing to significant or widespread adverse impacts, warranting the evaluation of safer alternatives.

Chemicals such as benzothiazoles (including 2-mercaptobenzothiazoles), chlorinated paraffins, octylphenol ethoxylates, and PAHs are also considered chemicals of potential concern by the DTSC's Candidate Chemicals List (CalSAFER).[35] Other tyre-derived chemicals of interest include other benzothiazoles, DPG, and MMM. Though these are still not in the Candidate Chemicals List, the DTSC recognises their potential concern for the aquatic environment, and hence, is seeking information related to these chemicals.[16]

There are some initiatives and regulations to limit or eliminate intentionally added microplastics in consumer products (for example, microbeads in cosmetic products). However, discussions surrounding tyres in this context typically focus on recycled rubber crumb materials (from EOL tyres), like those used in artificial turf, rather than the tyres themselves.

[30] https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/tsca-section-21

[31] https://www.epa.gov/newsreleases/epa-releases-information-states-and-tribes-can-use-protect-local-fish-toxic-tire

[32] https://6ppd.itrcweb.org/wp-content/uploads/2023/09/6PPD-Focus-Sheet-Web-Layout-9.pdf

[33] https://dtsc.ca.gov/scp/motor_vehicle_tires_containing_6ppd/

[34] https://dtsc.ca.gov/wp-content/uploads/sites/31/2023/11/Zinc-in-Tires-Rationale-Document_Final.pdf

[35] https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/06/Other-Tire-Derived-Chemicals-of-Interest-Summary-and-Questions-2021_ADA.pdf

Regulations related to emissions

The US EPA may advocate for tyres engineered for reduced wear if it starts setting standards for particle emissions, under the Clean Air Act, mirroring the National Emission Standards for Hazardous Air Pollutants (NESHAP) for rubber manufacturing.[36] Although there are no current EPA articles addressing standards for air particle emissions, the agency recognises the significance of the release of these particles (considered to be a significant form of microplastic), through its Trash Free Waters program.[37] However, the program seems to primarily concentrate on managing and controlling tyre wear pollution entering water ways rather than addressing it at the source or looking at it from air pollution perspective.

Regulations related to raw materials

The development of domestic sources of sustainable natural rubber is a key policy priority by the US Tire Manufacturers Association (USTMA) in 2024,[38] which is aimed at facilitating the expansion of advanced technologies and responsible infrastructure. This move could lead to changes in the use of natural rubber in tyres similar to the EU.

Whilst the US does not have a specific regulation or directives on sustainable product design, the concept of Sustainable Materials Management (SMM) is an approach endorsed by the US EPA and contributes to sustainability efforts in the US. Albeit not specific to tyres, it emphasises on reducing material use, redesigning materials to be less resource-intensive, and capturing “waste” as a resource for new materials and products.

Global

Global regulatory tools like the International Material Data System (IMDS) and Global Automotive Declarable Substance List (GADSL) developed by the Global Automotive Stakeholders Group (GASG),[39] play crucial roles in ensuring responsible material selection and transparency in the automotive supply chain. This harmonisation ensures consistency and clarity across regions and stakeholders.

The IMDS is the automobile industry’s material data system that functions to collect and archive information on substances used in automobile manufacturing, including tyres. It was developed to help the automotive industry comply with various regulations and standards related to hazardous substances, such as the EOL Vehicles Directive (Directive 2000/53/EC)[40] and REACH’s directive for substances in articles. It is an interactive data management system used in Japan, US, and Europe, where manufacturers can query the system to determine which components contain specific substances of interest to meet obligations. Manufacturers can also require suppliers to enter information on materials into the online system, with focus on substances contained in the final material. In the context of tyres, chemicals that react during the curing phase (e.g., polymers, sulfur, zinc, etc.) are generally excluded. An IMDS entry is obligatory for recycling rate management, management of substances of concern, and REACH compliance.

The GADSL is a detailed list of chemicals that manufacturers and suppliers must report. It covers substances that are expected to remain in materials at the point of sale, substances with reporting requirements, prohibited substances, and those likely to be regulated in the future.

[36] https://www.epa.gov/stationary-sources-air-pollution/rubber-tire-manufacturing-national-emission-standards-hazardous

[37] https://www.epa.gov/system/files/documents/2023-04/TFW%20TWPs%20Roundtable%20Summary%202022%20CLEAN%20March%2030%202023%20508%20compliant.pdf

[38] https://www.ustires.org/ustma-legislative-priorities-2024

[39] https://www.sciencedirect.com/science/article/pii/B9780128117705000042#s0035

[40] https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en

The GADSL ensures that suppliers and manufacturers comply with global regulations and make efforts to reduce the use of harmful substances. By consolidating various individual lists of declarable substances into a single comprehensive list, it simplifies the declaration process within the automotive industry. A list of chemicals related to tyres found in the GADSL can be found in the Appendix (Table A1).

3 Industry efforts in tyre design

HOW ARE TYRE INDUSTRY PLAYERS ADDRESSING AND PUBLICLY COMMUNICATING CHANGES IN TYRE DESIGNS TO MITIGATE TYRE WEAR AND CHEMICALS OF CONCERN?

Tyre manufacturers are prioritizing actions and initiatives to enhance their Environmental, Social, and Governance (ESG) practices, with a particular emphasis on streamlining activities to ensure greater sustainability and accountability. This commitment aligns with a broader industry trend where companies are increasingly focused on improving their ESG metrics as part of their long-term planning. Specifically, many companies have publicly shared their ambitions to make their products more sustainable and to ultimately manufacture their products using 100% sustainable materials by 2050. This commitment is also in line with their efforts to reduce climate impact and reduce waste by embracing circular economy practices for the product's entire life cycle. This means collaboration, creating innovative products, and managing resources efficiently.

A lot of these endeavours are linked to meeting established regulations and criteria presented in Section 2, such as the Corporate Sustainability Reporting Directive (CSRD), the Carbon Border Adjustment Mechanism (CBAM), and Extended Producer Responsibility (EPR), all designed to decrease environmental harm and foster sustainability in different sectors. Furthermore, schemes like the Euro 7 emission standards, EU Anti-Deforestation Regulation (EUDR), and the EU Raw Material initiative (EURMI) specifically address matters like reducing emissions, preventing deforestation, and managing resources, with a specific emphasis on rubber as a crucial resource.

INDUSTRY STRATEGIES/TRENDS

Leading tyre manufacturers[41] such as Bridgestone (Japan), Michelin (France), Continental (Germany), Goodyear (USA), and Pirelli (Italy) are making significant strides towards sustainability. Each company has set ambitious goals and implemented comprehensive strategies to minimise environmental impact and promote sustainable practices. While their communication and marketing of these initiatives may differ slightly, they share similar strategies to enhance sustainability throughout the tyre lifecycle. These strategies are in line with circular economy principles specifically on designing out waste and pollution and in keeping materials and products circulating at their highest value. Key actions include:

- Reevaluating the use of raw materials, from reducing quantity to exploring sustainable, environmentally benign or renewable alternatives.
- Developing durable tyres through enhanced design and new solutions.
- Maximizing the utilization of used tyres through retreading, repairing, and investing in recycling possibilities.

[41] Based on sales; https://www.tyrepress.com/wp-content/uploads/2023/06/Leading-Companies-2023.pdf

PROJECT EXAMPLES HIGHLIGHTING SUSTAINABILITY INITIATIVES THAT CAN RESULT IN CHANGES IN TYRE DESIGN

Reevaluating the use of raw materials

Companies like Bridgestone Group (Bridgestone and Firestone), Continental, Goodyear, Michelin and Pirelli have the most active agendas to eliminate the use of fossil-based raw materials and transition to producing tyres entirely from sustainable resources.

By reducing the quantity of raw materials used and opting for sustainable or renewable alternatives, waste and pollution are minimized from the outset. Furthermore, using renewable materials also means they can be reused or recycled more effectively, maintaining their value within the economy. A summary is provided in table 1. Please note that this information is based on initial findings, and some details may have been overlooked. Regardless, it offers a clear overview of the key themes covered.

- Bridgestone is reducing its consumption of raw materials through innovative approaches such as weight-saving technologies like ENLITEN[42] and Ologic[43] for tyre weight reduction, enhancing durability technologies to manufacture thinner yet durable tyres with fewer raw materials, and minimizing manufacturing process losses.
- Bridgestone is expanding and diversifying renewable resources, such as improving natural rubber productivity through innovative technologies and exploring alternative plants like guayule[44] for natural rubber supply. Collaborative projects with various partners (Versalis SPA, NRGene, and Kirin Holdings) aim to establish commercial operations for guayule cultivation and develop advanced genetic technologies to enhance productivity and scale.
- Michelin is actively exploring alternative and sustainable sources for tyre components, such as developing bio-derived raw materials like butadiene from sources like waste wood, rice husks, and corn stover through projects like the "Biobutterfly[45] project."
- Continental is focusing on sustainable materials and a responsible supply chain, ensuring the full traceability of natural rubber sources. Additionally, they are actively involved in the development of natural rubber derived from dandelions through the Taraxagum[46] project.
- Continental partnered with the Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) to enhance the sustainability of the natural rubber supply[47] chain in Indonesia. The partnership aims to establish criteria for sustainable production, train farmers, and enhance traceability in supply chains. The initiative is part of the German Federal Ministry for Economic Cooperation and Development develoPPP.de program,[48] aiming to improve rubber quality and supply chain efficiency and increase incomes for rubber tree cultivators.

[42] https://press.bridgestone-emea.com/bridgestone-brings-enliten-technology-to-motorsports-through-tyres-using-63-recycled-and-renewable-materials/#:~:text=%E2%80%9DBridgestone%20is%20passionate%20about%20contributing,our%20collaborative%20supply%20chain%20initiatives.

[43] https://www.bridgestone.com/technology_innovation/ologic/

[44] https://www.bridgestone.com/technology_innovation/natural_rubber/guayule/

[45] https://www.tirereview.com/michelin-bio-based-synthetic-rubber/

[46] https://www.continental-tires.com/about/sustainability/activities-and-initiatives/material-sourcing/taraxagum/

[47] https://www.continental.com/en/press/press-releases/continental-and-giz-committed-to-sustainability-in-the-natural-rubber-supply-chain/

[48] https://www.developpp.de/en/funding-programme/

- In partnership with Kordsa, an expert in reinforcement technologies, Continental Tyres introduced a sustainable adhesive technology called Cokoon[49] in 2020. Cokoon allows textile-reinforcing materials to bond with rubber compounds without using resorcinol and formaldehyde in the textile dip, thus minimizing environmental impact during production.
- Goodyear increased their use of bio-based oils to help replace petroleum-based oils in their products by 2040. An example is their use of soybean oil, which they use in their polymer and tyre manufacturing processes. The company is also using a silica product made of residual rice husk ash that can help deliver performance similar to sand-based silica.[50]
- Pirelli is enhancing the utilization of bio-based and recycled materials in tyre manufacturing while diminishing the use of fossil resources. Pirelli has introduced the world's first tyre incorporating FSC-certified natural rubber and rayon[51], affirming responsible plantation management practices that conserve biodiversity, support local communities, and maintain economic viability. The company engages in projects like the Hutan Harapan Project with BMW, promoting sustainably managed forests and controlled sources.
- Kumho Tyre (South Korea) is also working to develop new sustainable tyre ingredients using natural materials such as sunflower oil[52] and rice bran silica, as well as recycled materials such as rubber and carbon black.
- Yokohama (Japan) is currently working, together with partners in academia and industry, to develop synthetic rubber materials (butadiene and isoprene) from biomass[53] rather than fossil fuel.

Table 1. Summary of key themes from examples on reevaluating the use of raw materials discussed.

Company	Themes
Bridgestone	- Reducing raw material consumption - Expanding renewable resources - Developing sustainable materials - Introducing sustainable technologies
Michelin	- Expanding renewable resources - Developing sustainable materials
Continental	- Expanding renewable resources - Developing sustainable materials - Enhancing supply chain sustainability - Introducing sustainable technologies
Goodyear	- Developing sustainable materials - Increasing use of bio-based oils
Pirelli	- Developing sustainable materials - Utilizing recycled materials
Kumho Tyre	- Developing sustainable materials - Utilizing recycled materials
Yokohama	- Developing sustainable materials - Developing synthetic rubber

[49] https://www.continental.com/en/press/press-releases/2020-02-20-kordsa-cokoon-first-tires/

[50] https://corporate.goodyear.com/us/en/responsibility/sustainable-sourcing/sustainable-materials.html

[51] https://fsc.org/en/newscentre/general-news/the-worlds-first-fsc-certified-tyre-becomes-a-reality-thanks-to-pirelli-and#:~:text=Bonn%2C%2019%20May%202021%20%E2%80%93%20A,as%20well%20as%20other%20materials.

[52] https://www.tyrenews.co.uk/posts/kumho-tire-pioneers-80-sustainable-tyres-aiming-for-full-sustainability-by-2045

[53] https://www.y-yokohama.com/release/?id=3567&lang=en

Designing tyres to improve longevity and performance

Designing tyres for improved performance and longevity is crucial for minimizing waste and pollution from a circular economy perspective. By enhancing durability, tyres require less frequent replacement, thus extending the lifespan of the materials used. Examples include:

- Bridgestone is one of the leading innovators in silica-based tyre compositions[54] with 572 patents. The company has started using next-generation silica to increase the efficiency of its tyres. A new tread compound and tread pattern were created using this next-generation silica to increase wet traction and reduce rolling resistance. Other companies innovating in this technology domain are Cummins, Ford, and Dana.
- Bridgestone's ENLITEN[55] and Ologic[56] tyres utilise proprietary lightweight material in its tyre composition to achieve low rolling resistance for its tyres. The ENLITEN technology, for example, involves a proprietary compound mix that enables improved wear performance and a decreased tread depth, a reduced and reinforced inner liner thickness, and a new dedicated mould design concept.
- Michelin's eco-designed tyre, ePrimacy[57], has been designed with very low rolling resistance (slim belt) and a lower abrasion rate. It features a U-shape groove to maintain a high level of water evacuation for safety throughout the life of the tyre, and MaxTouch for longer tread life and better tyre longevity.
- Pirelli has focused on developing tyres with low energy consumption and reduced CO2 emissions, aiming to lower rolling resistance without compromising safety. This is evidenced by products like the Eco-safety design and PZERO-E tyre[58], the latter of which has achieved the highest rating in all parameters of the EU tyre label. This success is due to the use of specialised rolling resistance compounds and a unique tread pattern that also enhances wet braking performance. Moreover, the company focuses on manufacturing low-wear rate tyres to diminish particle emissions, aligning with anticipated Euro 7 compliance standards. This includes projects enhancing the biodegradability of tyre particles[59], highlighting the significance of utilizing natural rubber over synthetic alternatives.
- Sentury[60] Tyre, Qingdao Huagao, Shangdong[61] Hengyu, and Vitorria have all launched graphene tyres – the earliest record being 2015 for Vitorria. The incorporation of graphene was suggested to improve rolling resistance, achieve better mileage, and decrease tyre wear by 25%.
- ZC Rubber[62] (China) focuses on R&D of green tyres, operating under a low carbon development concept. They lower the rolling resistance of tyres using silica compounds and a radial structure.

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[54] https://www.just-auto.com/data-insights/innovators-silica-based-tyre-compositions-automotive/?cf-view

[55] https://press.bridgestone-emea.com/bridgestone-brings-enliten-technology-to-motorsports-through-tyres-using-63-recycled-and-renewable-materials/#:~:text=%E2%80%9DBridgestone%20is%20passionate%20about%20contributing,our%20collaborative%20supply%20chain%20initiatives.

[56] https://www.bridgestone.com/technology_innovation/ologic/

[57] https://www.michelin.com.au/auto/advice/choose-tyres/eco-designed-tyre

[58] https://press.pirelli.com/pirelli-presents-three-new-p-zero-tyres-at-the-goodwood-festival-of-speed/

[59] https://www.pirelli.com/global/en-ww/life/people/interviews/the-shift-to-sustainability-is-like-a-wheel-and-it-s-moving-faster-and-faster-130042/

[60] https://www.tyrepress.com/2016/10/sentury-electrostatic-graphene-tyre-breaks-through-performance-triangle/

[61] https://www.tyrepress.com/2016/10/shangdong-hengyu-making-graphene-tyres/

[62] https://www.zc-rubber.com/index.php/development/environmental_protection

Table 2. Summary of key themes from examples on designing tyres to improve longevity and performance discussed.

Company	Themes
Bridgestone	- Innovating in silica-based tyre compositions - Utilizing lightweight materials - Developing eco-designed tyres
Michelin	- Developing eco-designed tyres
Pirelli	- Developing eco-designed tyres - Focusing on low energy consumption & CO2 emissions
Sentury Tyre, Qingdao Huagao, Shandong Hengyu, Vittoria	- Using graphene in tyres
ZC Rubber	- R&D on green tyres

Maximizing the utilization of used tyres

Leading tyre manufacturers are advancing sustainability through innovative utilization of used tyres. Bridgestone focuses on recycling and retread technologies, while Continental's Conti GreenConcept emphasizes renewable materials and retreading. Michelin invests in repurposing waste into new tyre components, and Goodyear, Pirelli, Kumho Tyre, and Yokohama are integrating sustainable and recycled materials into their products. These activities help prevent tyres from becoming waste prematurely and maintain their value within the economy.

- Bridgestone emphasizes the importance of recycling and efficiently utilizing resources by implementing strategies like the EVERTYRE[63] initiative, which transforms used tyres into raw materials for new tyre production. Collaborative efforts with LanzaTech NZ, Inc. for carbon capture, and partnerships for post-consumer waste management play a crucial role in achieving sustainability goals. Additionally, the company explores retread technologies, repair solutions, and the increased utilization of recovered carbon black (DE-Black[64] from Delta Energy) through various initiatives.
- Continental introduced the Conti GreenConcept[65], a lightweight tyre with a high percentage of traceable, renewable, and recycled materials, an innovative design that saves resources, and a durable tread. The tyre uses 100% Taraxagum natural rubber for its tread compound. The concept allows for multiple retreading with low time and material investment. They emphasize renewing and recycling tyres as part of the ContiLifeCycle initiative.
- Michelin promotes the effective utilization of used tyres by producing carbon black from EOL tyres through initiatives like Enviro. Moreover, Michelin invests in recycling technologies to repurpose waste materials into new tyres, such as producing regenerated styrene from waste polystyrene (e.g., yogurt pots, food containers, plastic packaging) through projects with Pyrowave[66] and utilizing PET plastic to create regenerated textiles in collaboration with Carbios[67].

[63] https://www.bridgestone.com/products/evertireinitiative/

[64] https://www.bridgestoneamericas.com/en/press-release-details.en.2019.Bridgestone-Brings-First-At-Scale-Use-of-Recovered-Carbon-Black-to-Tire-Market

[65] https://www.continental-tires.com/about/technologies-and-innovations/concept-tires/conti-greenconcept-2021-/

[66] https://www.pyrowave.com/en/project/industrial-development/michelin-x-pyrowave

[67] https://www.carbios.com/en/carbios-and-michelin-developing-100-sustainable-tires/

Table 3. Summary of key themes from examples on maximizing the utilization of used tyres discussed.

Company	Themes
Bridgestone	- Recycling and utilizing used tyres (EVERTYRE initiative) - Carbon capture (LanzaTech NZ, Inc.) - Post-consumer waste management - Retread technologies - Repair solutions - Increased utilization of recovered carbon black (DE-Black from Delta Energy)
Continental	- Recycling and utilizing used tyres (ContiLifeCycle initiative) - Use of traceable, renewable, and recycled materials (Conti GreenConcept) - Multiple retreading capability - Use of Taraxagum natural rubber
Michelin	- Recycling and utilizing used tyres (carbon black production from EOL tyres through Enviro) - Repurposing waste materials (regenerated styrene from waste polystyrene via Pyrowave) - Utilizing PET plastic for regenerated textiles (collaboration with Carbios)

Specific innovations and actions to mitigate tyre wear and chemicals of concern

Tyre wear

Reduction in tyre wear is also evident in the efforts of tyre manufacturers, who are also striving to produce tyres that are energy efficient (low rolling resistance).

- Michelin's eco-designed tyre, ePrimacy, which has been designed with very low rolling resistance (slim belt using less raw materials) also has lower abrasion rate that may indicate less tyre wear. The low abrasion rate is attributed to the advanced rubber compounds and the optimised patch and balanced design for even wear.
- Pirelli's PZERO Etyre designed with over 55% bio-based and recycled materials and low rolling resistance also has lower tyre wear compared to traditional Pirelli products. In addition to the advanced rubber compounds and the optimised patch design, these tyres also have a reinforced structure that helps maintain tyre shape and integrity, which reduces rate of wear over time.

6PPD replacements

Tyre manufacturers and raw material suppliers are also involved in finding alternatives to 6PPD due to growing concerns over its transformation product, 6PPD-Q.

- A global consortium of 30 tyre manufacturers mobilized by the US Tyre Manufacturers Association (USTMA) has been conducting an alternatives analysis for 6PPD in accordance with California's Safer Consumer Product Regulations. To date, the consortium identified 5 possible alternatives in their Stage 1 Alternatives Analysis Report[68] (2024) to undergo further evaluation in Stage 2. The alternatives proposed include 7PPD, IPPD, 77PPD, CCPD and specialized graphene (graphene nanoplatelets e.g., Prophene™). Most of these chemicals are phenylene diamines (PPDs) that are the most logical and possibly easiest to implement alternative. Although these compounds can also form quinone derivatives, preliminary data suggests these have lower acute toxicity. Graphene, on the other hand, is a non-PPD alternative that likely poses greater challenges in terms of incorporation into tyre chemistry. The following tyre manufacturers are members of the consortium: Bridgestone Americas, Inc.; Continental Tire the Americas, LLC; Giti Tire (USA) Ltd.; The Goodyear Tire & Rubber Company; Hankook Tire America Corp; Kumho Tire U.S.A., Inc.; Michelin North America, Inc.; Nokian Tyres, Inc.; Pirelli Tire North America; Sumitomo Rubber Industries; Toyo Tire Holdings of Americas Inc., and Yokohama Tire Corporation and USTMA's statistical affiliate members: Double Coin North America (CMA) LLC; Maxxis International USA; Nexen Tire America, Inc.; and Sailun Tire Americas.
- A 6PPD Alternatives Cooperative Research and Development Agreement (CRADA) between Flexsys[69], a global leader in high-quality rubber chemicals, and the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) was also started in 2023 to explore potential alternatives for 6PPD.
- Asahi Kasei[70] Corporation, a multinational Japanese chemical company, is also working to reduce 6PPD usage in rubber compounds, by improving the inherent ozone resistance of the rubber itself, while retaining the compatibility with other rubbers/materials. Asahi Kasei has developed a 'unique' hydrogenation catalyst and a novel production technology to achieve the controlled selective hydrogenation of styrene butadiene rubber (SBR). This improves ozone resistance and compatibility with other rubbers.
- Molecular Rebar Design, LLC (MRD) is a company established to develop and commercialize a breakthrough form of modified carbon nanotubes (CNTs), called MOLECULAR REBAR®. The company has been awarded a number of Small Business Innovation Research (SBIR) grants from the U.S. Environmental Protection Agency (EPA).[71] The US EPA, Phase I project will use MOLECULAR REBAR® CNTs (2023) to reduce or replace 6PPD in tyre compounds, targeting similar/better lifetime of tyres with less environmental impact.

[68] https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf

[69] https://flexsys.com/2023/flexsys-announces-6ppd-alternatives-cooperative-research-development-agreement-with-usda-ars/

[70] https://www.european-rubber-journal.com/article/2092496/e4s-vi-top-10-features-mix-of-new-and-established-projects

[71] https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/11459/report/0

Table 4. Summary of key themes from examples on tyre wear reduction and 6PPD replacements.

Category	Company/Initiative	Details
Tyre Wear Reduction	Michelin	- Eco-designed tyre ePrimacy - Very low rolling resistance - Lower abrasion rate - Advanced rubber compounds - Optimised patch and balanced design for even wear
	Pirelli	- PZERO E tyre - Over 55% bio-based and recycled materials - Low rolling resistance - Lower tyre wear - Reinforced structure to maintain shape and integrity
6PPD Replacements	US Tyre Manufacturers Association (USTMA) Consortium	- 30 tyre manufacturers - Alternatives analysis for 6PPD - Stage 1 identified 5 alternatives: 7PPD, IPPD, 77PPD, CCPD, specialized graphene (Prophene™) - Phenylene diamines (PPDs) and graphene being evaluated
	Flexsys and USDA-ARS	- 6PPD Alternatives Cooperative Research and Development Agreement (CRADA) - Exploring potential alternatives for 6PPD
	Asahi Kasei Corporation	- Reducing 6PPD usage by improving ozone resistance - Unique hydrogenation catalyst and novel production technology for controlled selective hydrogenation of SBR
	Molecular Rebar Design, LLC (MRD)	- Developing MOLECULAR REBAR® CNTs - Small Business Innovation Research (SBIR) grants from US EPA - Reducing or replacing 6PPD - Targeting similar/better tyre lifetime with less environmental impact

4 Research initiatives in tyre design

WHAT ONGOING RESEARCH INITIATIVES AND COORDINATED EFFORTS ARE DRIVING CHANGES IN TYRE DESIGN GLOBALLY?

Research innovations in tyre design are being driven by customer expectations (performance, safety, electric vehicle compatibility), environmental concerns (air and particulate emissions, contaminants), sustainability goals (raw materials, circularity), and evolving government regulations (anti-deforestation laws, bans on 6PPD). These innovations could mean changes to tyre structure (e.g., airless designs, redesigns for improved recyclability) and/or tyre composition (e.g., advanced fillers, eco-friendly materials, super-elastomers).

Several research collaborations and partnerships that are actively working on tyre research and development can be categorised into:

- **Academic / Government grant-funded:** Universities and research organisations collaborating through government or non-for-profit organization grants. These partnerships focus on fundamental research with the intent of industrial application.
- **Industry-led partnerships:** Collaborations between industry and academic institutions, research organisations, and/or startup companies to co-develop science and technology and gain access to the latest research.
- **Larger consortiums**: Multi-organisation collaborations, including industry, academic institutions, and government agencies, that conduct research and development projects, sharing resources and expertise.

These collaborations range from straightforward research projects to more complex open research centres involving multiple institutions. Indeed, several fruitful partnerships exist between universities, national laboratories, and industry, especially at the fundamental level. These initiatives create a foundation for rapid advancements in new tyre technology concepts. Below are examples of these collaborations, highlighting their key focus areas and their influence on tyre design.

ACADEMIC / GOVERNMENT GRANT-FUNDED RESEARCH

Academic efforts in tyre design encompass a broad range of fundamental studies aimed at optimizing performance, enhancing safety, and addressing environmental concerns. While numerous papers focus on tyre research from a materials science perspective—covering new polymers, additives, and testing methodologies—few organized efforts have been identified. The majority of these organized efforts are funded by US agencies.

Range of design topics

- The US National Science Foundation Center for Tyre Research (CenTiRe)[72] (2024) is a Centre built by the University of Akron and Virginia Polytechnic Institute and State University under the NSF's Industry-University Cooperative Research Centers Program with at least 21 affiliated member organisations. The centre is dedicated to researching tyre and tyre/vehicle materials, physics (including modelling), testing, sustainability, and manufacturing. This centre capitalizes on the expertise of the universities in material science. Some of their current projects include investigating the effects of rubber aging on tyre lifespan using both modelling and experimental methods; researching surface migration of 6PPD and designing novel sustainable antiozonants and antioxidants for rubber formulations; behaviour of heterogeneous fillers in rubber compounds and their influence on tyre properties; and modelling nanoscale tyre-road interface to improve adhesion and reduce sliding friction.

6PPD replacement and energy efficiency

- Molecular Rebar Design, LLC (MRD) that received grants through the US EPA for 6PPD replacements, also has a grant with the Department of Energy (2022)[73]. The DoE project aims to produce longer-lasting, more energy-efficient electric vehicle tyres using CNTs. The project is currently in Phase II where a commercially viable product form of the CNT material developed in Phase I will be created and will be used by Goodyear to build a prototype.

Computer simulations

- The US Department of Energy has awarded a significant grant to Coreform[74] (2024), a computer-aided engineering company, to develop computer simulation processes aimed at enhancing the advanced tyre industry. Predictive simulation for tyre tread designs can lower product development costs and speed up the adoption of electric and self-driving cars. The project aims to help the tyre industry create innovative tread patterns that reduce noise and improve energy efficiency. Instead of resorting to physical testing of prototypes, isogeometric analysis will allow tyre manufacturers to test new designs much more quickly.

Table 5. Examples of academic/government grant-funded research that are driving tyre design.

Organization/Project	Details
US National Science Foundation Center for Tyre Research (CenTiRe)	- Research on tyre/vehicle materials, physics, testing, sustainability, and manufacturing - Projects on rubber aging, 6PPD surface migration, heterogeneous fillers, nanoscale tyre-road interface
Molecular Rebar Design, LLC (MRD)	- Grants from US EPA and Department of Energy - Phase II project on energy-efficient electric vehicle tyres using CNTs - Prototype development with Goodyear
Coreform	- DOE grant for developing computer simulation processes - Enhancing advanced tyre industry with predictive simulation for tread designs

[72] https://www.centire.org/

[73] https://www.molecularrebar.com/2022/09/29/mrd-awarded-sbir-doe-phase-ii-grant/

[74] https://coreform.com/company/news/2024/tirephaseii/

INDUSTRY PARTNERSHIPS / COOPERATION

- Several industry-led partnerships and collaborations currently exist between tyre manufacturers, universities, and smaller private industries. Individual manufacturers often engage with different organizations to focus on research and development in various areas. For example, Bridgestone has at least three ongoing partnerships: with the Luxembourg Institute of Science and Technology to develop fillers, with Kao (a Japanese chemical company) for silicon dispersants, and with Arlanxeo and Solvay for the development of synthetic rubber with tailor-made silica.

Fillers and improving durability of rubber

- Yokohama Rubber[75], together with Shinshu University, (2023) develops rubber material with crack resistance from nanoparticle-based tough polymers that can be recycled without deterioration.
- Goodyear and researchers from the Luxembourg Institute of Science and Technology[76] (LIST, 2019) have joined forces in a strategic partnership to focus on overcoming the challenges in future tyre technology. The 6-year program will focus on developing fillers to enhance the mechanical properties of tyre rubber or reduce its weight, designing and producing synthetic macromolecules tailored for specific tyre applications, studying the effects of small amounts of additives on polymer processing and final properties, and creating novel methods for materials characterization and testing.
- A prominent global producer of silica, Evonik, has initiated a strategic partnership with the Pörner Group (Austria) and Phichit Bio Power Co., Ltd. (Thailand)[77] to provide sustainable ULTRASIL® precipitated silica to tyre manufacturers. The primary raw material utilized for this environmentally friendly silica is sodium silicate, sourced from rice husk ash (RHA), a byproduct of agriculture, and manufactured entirely using renewable energy sources. Silica plays a crucial role as the main component in energy-efficient tyres, contributing to a potential reduction in fuel consumption of up to eight percent when compared to standard passenger car tyres. Evonik's Product Line Rubber Silica received Pirelli's Award in the Quality category as the best out of 15,000 global suppliers.
- Kao and Bridgestone are collaborating[78] to develop a silica dispersion improver that enhances the blending of silica with rubber, improving fuel efficiency and wet grip in tyres. This plant-derived dispersant is used in Bridgestone's Ecopia EX20 tyre, boosting wet-braking performance by 12% without sacrificing fuel efficiency, and supports sustainable automotive development.
- Bridgestone is also collaborating with Arlanxeo (synthetic rubber producer) and Solvay[79] to launch Techsyn, a new tyre technology aimed at boosting environmental performance. Techsyn combines synthetic rubber with tailor-made silica, offering 30% better wear efficiency and improved road resistance, thus extending tyre lifespan by up to 30%. This reduces material consumption, fuel use, and CO2 emissions. Bridgestone is preparing to implement Techsyn for mass production across various tyre categories and vehicles.

[75] https://www.y-yokohama.com/release/pdf/2023062315tr001.pdf

[76] https://www.fnr.lu/research-with-impact-fnr-highlight/joining-forces-tires-of-the-future/

[77] https://www.silica-specialist.com/en/service-center/press-releases/new-cooperation-enables-evonik-to-provide-tire-industry-with-silica-made-from-biobased-raw-materials-178045.html

[78] https://www.kao.com/global/en/innovation/research-development/product-development/chemicals/silica-dispersion/

[79] https://press.bridgestone-emea.com/en/bridgestone-arlanxeo-and-solvay-launch-techsyn-to-give-tyres-unrivalled-strength-and-environmental-performance/

Oils

- Partnership between the United Soybean Board and the Goodyear Tyre and Rubber Company[80] (2021) is committing to source sustainably produced U.S. soybean oil, and phase out petroleum-derived oils from its products by 2040.

6PPD replacement

- A 6PPD Alternatives Cooperative Research and Development Agreement (CRADA)[81] between Flexsys, a global leader in high quality rubber chemicals, and the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) was also started in 2023 to explore potential alternatives for 6PPD.

Recycling

- Enviro Systems (Enviro) together with Chalmers University of Technology in Sweden[82] (2023) are working to reduce the carbon footprint of West Sweden's chemicals industry. The partnership is leveraging combined knowledge to develop the next generation of Enviro's pyrolysis-based recycling technology. Sub-projects include transition to renewable and recovered raw materials and recovery of complex polymers. Michelin has also teamed up with Enviro[83] (2021) to build Michelin's first tyre recycling plant, enabling it to recover materials such as carbon black, pyrolysis oil, steel, gas and other reusable materials from EOL tyres.

Tyre monitoring/sensing

- Goodyear Ventures with San Francisco-based Voyomotive L.L.C.[84] (2021) is working on pilot tyre-monitoring solutions. These solutions enable predictive maintenance by capturing and analyzing relevant tyre performance data, such as tyre pressure. The cloud-based service delivers pertinent information to vehicle owners and fleet operators, enhancing safety and efficiency.
- TDK Corporation and The Goodyear Tyre & Rubber Company[85] (2024) have joined forces to advance next-generation tyre solutions. Their goal is to accelerate the development and adoption of integrated intelligent hardware and software into tyres and vehicle ecosystems. The collaboration aims to bring a robust tyre sensing system to market, combining TDK's expertise in software, sensors, and electronic components with Goodyear's tyre development know-how and intelligent solutions.

Environmental impact of tyres

- Michelin and CNRS, Université Clermont Auvergne[86] (2023), who have been working on polymer and polymer nanocomposites over the last 10 years, recently established the BioDLab joint research laboratory to study the degradation and biodegradation of tyre rubber.

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[80] https://www.unitedsoybean.org/hopper/collaborative-checkoff-partnership-leads-to-sustainable-soybean-oil-commitment-from-goodyear/

[81] https://flexsys.com/2023/flexsys-announces-6ppd-alternatives-cooperative-research-development-agreement-with-usda-ars/

[82] https://www.packaginginsights.com/news/enviro-and-chalmers-university-target-next-gen-recycling-to-decarbonize-swedens-chemical-industry.html

[83] https://www.greenbiz.com/article/how-michelin-and-bridgestone-are-accelerating-green-tire-innovations

[84] https://news.goodyear.eu/goodyear-and-voyomotive-collaborate-on-tire-intelligence-for-vehicle-efficiency/

[85] https://www.tdk.com/en/news_center/press/20240109_01.html

[86] https://www.cnrs.fr/en/press/michelin-cnrs-and-luniversite-clermont-auvergne-join-forces-understand-science-tyre-wear

Range of topics

- Pirelli and University of Milan[87] (2021) have a joint labs program that works on a range of technological innovations in tyres.

  The program will use simulators to optimize tyre development and testing, reducing lead times and enhancing OEM collaborations.

- The research will also be undertaken on polymer modification, nanofillers, eco-friendly materials, and the use of open-source modelling for textile reinforcements. Noise testing, tyre aerodynamics, and automated tread modelling will also be covered.

[87] https://www.automotivetestingtechnologyinternational.com/news/pirelli-and-university-of-milan-to-continue-virtual-tire-development-research.html

Table 6. Examples of industry partnerships/cooperation that are driving tyre design.

Organization/Project	Details
Bridgestone Partnerships with Luxembourg Institute of Science and Technology, Kao, Arlanxeo, and Solvay	- Focus on fillers, silicon dispersants, synthetic rubber, Techsyn technology
Yokohama Rubber Collaboration with Shinshu University	- Developing crack-resistant rubber material with nanoparticle-based polymers
Goodyear Partnership with Luxembourg Institute of Science and Technology	- Developing fillers, synthetic macromolecules, polymer processing, and materials characterization
Evonik Partnership with Pörner Group and Phichit Bio Power Co., Ltd.	- Providing sustainable ULTRASIL® precipitated silica - Using sodium silicate from rice husk ash
Kao Collaboration with Bridgestone	- Developing silica dispersion improver for fuel efficiency and wet grip
United Soybean Board and Goodyear	- Sourcing sustainably produced U.S. soybean oil - Phasing out petroleum-derived oils by 2040
Flexsys and USDA-ARS	- CRADA to explore alternatives for 6PPD - Developing alternatives for rubber compounds
Enviro Systems and Chalmers University	- Developing next-generation pyrolysis-based recycling technology - Recovering complex polymers and transitioning to renewable materials
Michelin and Enviro Systems	- Building Michelin's first tyre recycling plant - Recovering carbon black, pyrolysis oil, steel, gas, and other materials from EOL tyres
Goodyear Ventures and Voyomotive L.L.C.	- Pilot tyre-monitoring solutions - Predictive maintenance with cloud-based service for tyre performance data
TDK Corporation and Goodyear	- Developing next-generation tyre solutions - Integrating intelligent hardware and software into tyres and vehicle ecosystems
Michelin and CNRS, Université Clermont Auvergne	- BioDLab joint research laboratory - Studying degradation and biodegradation of tyre rubber
Pirelli and University of Milan	- Joint labs program - Working on polymer modification, nanofillers, eco-friendly materials, and open-source modelling

COLLABORATIVE EFFORTS AND CONSORTIA

Whilst industry-led partnerships appear to focus on key tyre components (fillers, polymers, oils, additives, etc.), larger collaborative efforts and consortiums tackle areas focussed on sustainability (in rubber sources and EOL tyres), chemicals of concern, and particle emissions.

Rubber sources

- Global Platform for Sustainable Natural Rubber (GPSNR)[88] (2022) is a multi-stakeholder platform that aims to transition the entire value chain towards greater sustainability. The platform has brought together manufacturers, NGOs, and producers including smallholder farmers and a wide range of other industry participants, with a total of more than 100 members. The Global Platform works to address industry issues including forest sustainability, water management and labour, and land and human rights associated with the production of natural rubber.
- The International Rubber Study Group (IRSG)[89] is aimed at improving transparency in the global rubber market and enhancing international cooperation on rubber-related issues. As the largest worldwide community in the rubber economy, IRSG focuses on market transparency and cooperation, though it is not directly involved in research.
- The Biomass Research and Development Initiative Consortium[90] (2016), led by Cooper Tyre, is formed by other academic partners: Clemson University, Cornell University, PanAridus, and the Agricultural Research Service of the US Department of Agriculture and the US Department of Energy. The project aimed to develop manufacturing processes for producing solid rubber from the guayule plant for tyre applications and evaluate its residual biomass for fuel. The consortium sought to replace synthetic rubbers and Hevea natural rubber with guayule biopolymers and focused on the plant's genomic and agronomic development and the sustainability impact on the American southwest. (Completed in 2017)

6PPD replacement

- A global consortium of 30 tyre manufacturers mobilized by the US Tyre Manufacturers Association (USTMA)[91] (2024) has been conducting an alternatives analysis for 6PPD in accordance with California's Safer Consumer Product Regulations. To date, the consortium identified 5 possible alternatives in their Stage 1 Alternatives Analysis Report[92] (2024) to undergo further evaluation in Stage 2. The alternatives proposed include 7PPD, IPPD, 77PPD, CCPD and specialized graphene (graphene nanoplatelets e.g., Prophene™). The majority of these chemicals are phenylene diamines (PPDs) that are the most logical and possibly easiest to implement alternative, though they can also form quinone derivatives, preliminary data suggests these have lower acute toxicity. Graphene, on the other hand, is a non-PPD alternative that likely poses greater challenges in terms of incorporation into tyre chemistry.

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[88] https://sustainablenaturalrubber.org/

[89] https://www.rubberstudy.org/

[90] https://renewable-carbon.eu/news/cooper-tire-and-consortium-partners-report-significant-progress-on-grant-to-develop-guayule-polymer-for-tire-applications/

[91] https://www.ustires.org/largest-global-tire-industry-consortium-releases-preliminary-6ppd-alternatives-analysis-report

[92] https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf

EOL tyres / recycling

- The BlackCycle Project[93] (2020) was funded by the EU Horizon 2020 to explore recycling end of-life tyres into new tyres, i.e., producing high-value/technical second raw materials. This project consortium, led by Michelin, is formed by 7 industrial partners, and 5 Research & Technological Organizations to assess the entire value chain. It involves multiple stages from collection (Aliapur), ground and sorted (Hera and Estato), pyrolysis (Pyrum, CSIC, CPERI/CERTH), production of carbon black (Orion), and tyre manufacture (Michelin).
- The WhiteCycle Project[94] (2022) is an innovative European initiative aimed at processing and recycling complex waste containing textile made of plastic. Coordinated by Michelin, this unique consortium brings together 16 public and private European organizations. Their main goal is to develop circular solutions that convert such waste into high-value products, contributing to a more sustainable and circular economy.
- The USTMA recently (May2024) announced the creation of the Tyre Recycling Foundation[95], which will secure funding and allocate grants for research, education, intervention and demonstration targeting critical knowledge and research gaps within the US tyre recycling supply chain. The foundation that aims to recycle 100% of EOL tyres into circular, sustainable markets. At the moment, focus is on accelerating adoption of rubber modified asphalt.
- The LIFE programme, EU's funding instrument for the environment and climate action, also supported the Italian project Life Green Vulcan[96] (2020) which aims to revolutionise tyre recycling and reuse with its innovative and environmentally-friendly rubber de-vulcanisation process. This project involves six partners, including tyre manufacturers, universities, and small and medium-sized enterprises (SMEs).

Impacts / tyre emissions

- The World Business Council for Sustainable Development's Tire Industry Project[97] (TIP) is a prominent global initiative to address sustainability issues in the tyre industry. This initiative involves 10 major companies to address the potential impacts of tyres on human health and the environment. At this stage, the research appears to focus on tyre and road wear particles (TRWP), specifically in understanding their impacts on human health and the environment. Specific research on producing tyres that emit less does not appear to be covered in this initiative.
- The European Tyre and Rubber Manufacturers' Association (ETRMA) launched a multistakeholder initiative facilitated by CSR Europe[98] to tackle issues with TRWP, including mitigation strategies. However, similar to the TIP, these strategies primarily focus on managing released particles rather than producing tyres that emit fewer particles.

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[93] https://blackcycle-project.eu/about-the-project/

[94] https://www.whitecycle-project.eu/

[95] https://www.ustires.org/ustma-champions-tire-circularity-launch-tire-recycling-foundation-nationwide-push-rubber-modified

[96] https://www.lifegreenvulcan.eu/

[97] https://www.wbcsd.org/Sector-Projects/Tire-Industry-Project

[98] https://www.csreurope.org/trwp?rq=european%20trwp%20platform

Table 7. Examples of collaborative efforts and consortia that are driving tyre design.

Organization/Project	Details
Global Platform for Sustainable Natural Rubber (GPSNR)	- Multi-stakeholder platform for sustainable natural rubber - Addressing forest sustainability, water management, and human rights
International Rubber Study Group (IRSG)	- Focus on market transparency and international cooperation - Not directly involved in research
Biomass Research and Development Initiative Consortium	- Developing guayule biopolymers for tyres - Evaluating residual biomass for fuel - Completed in 2017
USTMA Global Consortium	- Alternatives analysis for 6PPD - Identified 5 alternatives for further evaluation: 7PPD, IPPD, 77PPD, CCPD, graphene
BlackCycle Project	- EU Horizon 2020 funded - Recycling end-of-life tyres into new tyres - Assessing the entire value chain
WhiteCycle Project	- European initiative for recycling complex waste - Converting textile waste into high-value products
Tyre Recycling Foundation (USTMA)	- Securing funding and grants for tyre recycling research - Focus on accelerating adoption of rubber modified asphalt
Life Green Vulcan (EU LIFE Programme)	- Innovative tyre recycling with environmentally-friendly de-vulcanisation process
World Business Council for Sustainable Development's Tire Industry Project (TIP)	- Addressing sustainability issues in tyre industry - Research on tyre and road wear particles (TRWP) and their impact
European Tyre and Rubber Manufacturers' Association (ETRMA)	- Tackling TRWP issues - Mitigation strategies for released particles

FOCUS AREAS

Collaborations and partnerships with tyre manufacturers are essential to facilitate meaningful advancements, as the tyre industry is the primary end-user of tyre design research. Hence, it is fitting that the scope of research supported through government grants, partnerships, and consortiums aligns with the focus areas identified by tyre manufacturers (Section 3). Below are some examples of some of these identified areas.

- The Center for Tire Research (CenTiRe) (2024) by the University of Akron and Virginia Polytechnic Institute and State University covers a range of research areas that benefit the tyre industry with a focus on fundamental issues. The emphasis on sustainability is evident, with concepts such as “green tyres”[99] and “bio-based tyres” frequently appearing in academic papers. “Green” may mean the use of renewable resource-based polymer materials, eco-friendly modification of macromolecules to achieve the required properties, and complete and partial replacement of harmful components. Indeed, these concepts may dominate the industry by 2025-2030.

[99] https://link.springer.com/article/10.1007/s00289-022-04445-2

- In addition to finding more sustainable natural rubber sources and incorporating ELTs back into tyres, research is actively exploring replacements for traditional fillers, processing oils, and additives (such as accelerators, activators, and anti-ozonants). The effective use of silica as a reinforcing filler for rubber compounds, to replace or reduce the use of carbon black, has been featured in partnerships with Pirelli and Bridgestone. Improving tyre design to reduce wear is being pursued through innovations in tread designs, polymers, fillers, and nanomaterials. Some of these innovations may provide self-healing properties and extend the lifespan of commercial tyres. For example, incorporating carbon-derived fillers such as graphene oxide[100] and ground tyre rubber[101] has been shown to enhance the healing capacity of elastomeric matrices without compromising mechanical performance. Additionally, several initiatives are investing in finding replacements for 6PPD, which as reported previously (Section 3) tend to be (US) government led.
- Complementing all this research is tyre modelling, which is also gaining traction for faster tyre development and testing. These simulations enable multiscale compound design, allowing multiple performance properties to be optimized simultaneously. For example, simulation techniques, particularly finite element analysis, are being used to predict and reduce rolling resistance[102] and durability[103].

With tyre manufacturers forming multiple partnerships and developing proprietary formulations, significant diversification of tyres is occurring, which can pose challenges with tyres management.

OTHER RELEVANT REPORTS

A recent report published by Smithers' on the future of global tyres[104] identifies key technologies expected to drive innovations in tyre manufacturing over the next 20 years. The report divides these technologies into two categories:

Enabling Technologies: These are external advancements crucial for developing tyre-specific innovations. They include:

- Sustainability Initiatives: Efforts to reduce the environmental impact of tyre production.
- Sensor/RFID Technology: Integration of sensors and RFID for tyre condition monitoring.
- Battery Technology: Advances in batteries that influence tyre design for electric vehicles.
- Modelling and Simulation: Use of advanced computational methods to design and test tyres.
- Biotechnology: Application of biological processes in tyre manufacturing and recycling.

Tyre-Specific Technologies: These are direct innovations in tyre design and functionality. They include:

- Non-Pneumatic Tyres: Airless tyres that eliminate the risk of punctures.
- Smart Tyres: Tyres with embedded technology for real-time monitoring and data transmission.
- Chemicals of Concern: Focus on identifying and reducing harmful chemicals in tyre production.
- Self-Healing Polymers: Materials that can repair themselves to extend tyre life.
- Recycling of Used Tyres: Techniques for efficient recycling of old tyres.

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[100] https://www.scipedia.com/public/Utrera-Barrios_et_al_2022a

[101] https://www.mdpi.com/2073-4360/11/12/2122

[102] https://iopscience.iop.org/article/10.1088/1757-899X/1234/1/012002

[103] https://www.roadsafellc.com/NCHRP22-24/Literature/Papers/Tire_modeling/Making%20FEM%20Tire%20Model%20and%20Applying%20It%20For%20Durability%20Simulation.pdf

[104] https://www.smithers.com/services/market-reports/transportation/global-tire-markets-to-2024

- EV Tyres: Specialized tyres designed to meet the demands of electric vehicles.

Note that some of these are overlapping technologies, e.g., EV tyres containing self-healing polymers and monitoring technologies. The report provides a comprehensive outlook on the future of tyre design, emphasizing sustainability, technological integration, and innovation. However, detailed information is not available in the open-access version and may require access to the full report for more in-depth insights.

5 Regional approaches to eliminating chemicals of concern

WHILE THE US AND EUROPE ARE ACTIVELY ENGAGING IN REGULATORY MEASURES TO ELIMINATE CHEMICALS OF CONCERN, WHAT IS THE STANCE OF THE UK, CANADA, NZ, AND ASIA? ARE THESE REGIONS MORE PROACTIVE THAN AUSTRALIA, OR ARE THEY ADOPTING A MORE PASSIVE APPROACH?

The regulatory stance of the UK, Canada, New Zealand, and various Asian countries towards the removal of hazardous chemicals differs, showing varying levels of proactivity across different regions. Presented below are brief overviews of the chemical regulations in various countries, which are summarised in Table 8.

OVERVIEW OF CHEMICAL REGULATIONS

United Kingdom

The UK has implemented the UK REACH regulation following its exit from the EU. The UK REACH and EU REACH are similar in their core principles and structure, ensuring high levels of protection for human health and the environment aiming to control and phase out chemicals of high concern. However, perhaps due to the comparative lack of regulatory capacity and resources to assess risk in the UK since its departure from the EU, the UK appears to be considering far fewer protective controls, hazardous substances, or restrictions than the EU.[105] The UK seeks to take an alternative approach to chemical regulation to avoid redundancy and complement EU's approach. While the EU REACH employs a hazard-based approach, identifying chemicals as "Substances of Very High Concern" based solely on their hazardous properties and advocating for their avoidance as much as possible, the UK REACH employs a risk-based approach. This approach considers both exposure and hazard, potentially leading to significant differences in the regulation of thousands of substances.[106] The regulatory landscape in the UK appears to be dynamic, particularly as it seeks to diverge from EU REACH, while also aiming alignment in certain areas post Brexit.

Canada

Canada's risk-based approach to regulating chemicals of concern is multifaceted, involving several regulatory frameworks and strategic initiatives. The Chemicals Management Plan (CMP) assesses and manages risks to human health and the environment posed by chemical substances. In conjunction, the New Substances Notification Regulations (NSNR) require pre-market risk assessments for new chemicals and organisms, ensuring potential risks are evaluated before they enter the marketplace.[107] Under the Canadian Environmental Protection Act, 6PPD, for example, has been placed on the priority substance list for assessment[108].

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[105] https://setac.onlinelibrary.wiley.com/doi/10.1002/ieam.4941

[106] https://www.steptoe.com/en/news-publications/regulatory-landscape-in-the-eu-and-the-uk-key-considerations-in-2024.html

[107] https://doi.org/10.1016/j.envres.2021.112225

[108] https://ecojustice.ca/wp-content/uploads/2024/05/Ecojustice-Response-to-Request-to-Assess-6PPD-under-section-76-of-CEPA.pdf

New Zealand

New Zealand also follows a risk-based approach under the Hazardous Substances and New Organisms (HSNO) Act, which is a central piece of legislation that regulates the introduction and management of hazardous substances and new organisms in New Zealand. The act focuses on protecting human health and the environment by assessing the risks associated with these substances before they are approved for use. Although robust, it may be viewed as more focused on risk management through regulatory oversight than outright elimination of certain chemicals, unlike the more stringent measures seen in the EU or US.[109] This approach, similar to the regulation of pesticides, aims to mitigate potential risks through controlled use rather than complete elimination.[110] The regulatory framework under HSNO is evolving. For instance, the Psychoactive Substances Act 2013 introduces an innovative approach by shifting the burden of proof to manufacturers to demonstrate low risk for market approval, moving beyond traditional prohibition methods.[111]

Japan

Japan has a comprehensive and stringent, risk-based approach to managing and eliminating chemicals of concern, primarily through its Chemical Substances Control Law (CSCL) and the Industrial Safety and Health Act. Their approach to new chemical control is distinctive globally, implementing pre-manufacture evaluations for new chemicals, with a list of data requirements that strongly focus on biodegradation and bioaccumulation potential of the chemical.[112] Depending on the outcomes of these tests, ecotoxicity and toxicity studies may be necessary. Recent regulatory updates include tighter controls on specific high-risk chemicals, with enhanced requirements for the registration and evaluation of new chemicals and more rigorous data requirements for existing chemicals.[113]

China

China's Environmental Risk Assessment and Control of Chemical Substances law reflects a growing proactivity, aligning with international standards (e.g., EU REACH and TSCA) to control hazardous chemicals. It incorporates ideas and strategies from Western countries, where regulations often focus on market mechanisms and transparency of information. It is also influenced by its own governance model, the complex relationship between central and local governments, and the balance between the needs for environmental protection and economic growth.[114] The management of Substances of Very High Concern (SVHCs) is a critical focus, yet China faces obstacles due to insufficient advanced technological renovation and experience in risk administration.[115] On May 24, 2022, the China State Council issued an Action Plan on New Pollutants Governance ("Plan"), outlining a regulatory roadmap for managing new chemicals and strengthening enforcement for compliance.[116] The Plan outlines a framework for an environmental risk management system for chemicals, to be developed through future regulations. It aims to expand existing chemical regulatory programs and encourages local governments to implement risk assessments and create local control plans, rules, and standards for managing key chemicals.

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[109] https://nzpps.org/_journal/index.php/pnzppc/article/view/11353/11203

[110] https://dx.doi.org/10.2139/ssrn.3270393

[111] https://doi.org/10.1177/0269881113491441

[112] https://www.chemsafetypro.com/Topics/Japan/Japan_CSCL_Chemical_Substance_Control_Law.html

[113] https://www.meti.go.jp/policy/chemical_management/english/cscl/files/about/01CSCL_2021.pdf

[114] https://doi.org/10.1093/acrefore/9780199389414.013.418

[115] https://engine.scichina.com/doi/pdf/A7EE5D8F08554010AC208E3CB8CF2535

[116] https://www.bdlaw.com/publications/china-sets-out-a-regulatory-roadmap-to-control-new-chemicals/#:~:text=chemicals%20with%20high%20concern%20and,chemicals%20will%20be%20implemented%3B%20and

India

India’s draft National Chemical Policy aims to establish a comprehensive regulatory system. The policy is still evolving and focusing on developing a comprehensive regulatory framework, akin to the EU REACH. It will control the safe use of chemicals in India along the lines of EU REACH principles of “no data, no market” and achieve similar objectives including safety and accident preparedness from existing regulation on hazardous chemicals.[117]

Australia

Australia's approach to regulating chemicals of concern involves a multifaceted framework with various regulatory bodies and policies. The Australian Pesticides and Veterinary Medicines Authority (APVMA) and the Australian Industrial Chemicals Introduction Scheme (AICIS, formerly NICNAS) are responsible for regulating agricultural, veterinary, and industrial chemicals, respectively. While this framework is comprehensive, there are opportunities for enhancement such as improving coordination and streamlining processes. The current system could benefit from a more unified national program for monitoring chemical residues, a more expedited pace in chemical reviews, increased research on human health impacts, and more consistent risk management across states and territories.[118] Compared to the EU and US, Australia adopts a science and risk-based framework that is more balanced, with elements of both proactive and reactive stances for assessing chemicals depending on the specific chemical, data availability, and international regulatory trends.

Table 8. Overview of regional regulatory frameworks and proactivity levels in chemical management.

Region	Regulatory Framework	Proactivity level	Comments
UK	UK REACH	High	Aims to complement EU REACH; REACH in UK is fundamentally different to that in EU, where UK considers risk and EU considers hazard.
Canada	CMP, NSNR	High	Multi-faceted approach almost similar to the US
New Zealand	HSNO Act	Moderate	Regulatory landscape evolving, possible shift towards more aggressive elimination measures with push to acknowledge Māori values to better protect biodiversity and human health
Japan	CSCL	High	Implements pre-manufacture evaluations for new chemicals
China	Environmental Risk Assessment	Increasing	Evolving but challenges remain due to multiple influences
India	Draft National Chemical Policy	Developing	Draft policy to be implemented and regulatory framework to be established
Australia	AICIS	Moderate	Adopts a science and risk-based framework with elements of both precautionary and reactive stances

[117] https://www.reachlaw.fi/wp-content/uploads/2022/11/status_indiareach_gagan.pdf

[118] https://doi.org/10.3390/ijerph19116673

6 Summary of findings

GLOBAL REGULATIONS AND POLICIES THAT CAN INFLUENCE TYRE DESIGN

Both the EU and US are actively addressing specific chemicals of concern, particularly 6PPD, and recognize the importance of natural rubber as a valuable resource, alongside concerns about tyre emissions. However, regulatory approaches differ between regions. The EU demonstrates a proactive stance, addressing broader issues surrounding tyres, such as their assessment of amino-substituted diarylamines beyond just 6PPD. Through Euro 7, new emission standards for tyres intended for sale are being established, encouraging manufacturers to design tyres with lower particle emissions, addressing the issue at the source. Furthermore, the importance of circular economy, sustainability and responsible manufacturing is apparent in the EU, with a variety of policies/rules/directives/regulations. In contrast, the US approach appears more reactive. Their initial assessment of 6PPD does not encompass similar compounds that could serve as substitutes, and their strategy for managing tyre emissions focuses on controlling pollution from tyre wear entering waterways rather than addressing it at the source (tyres). And while sustainability is endorsed, it does not appear to be a strong focus in terms of policies/rules/directives/regulations. Indeed, these regulations may influence future tyre designs in a way that is protective of natural resources, environment and human health. In compliance with regulations, future tyres may undergo changes, including:

- Changes to the natural rubber used;
- Increased incorporation of recycled materials;
- Engineering for improved durability/reduced wear;
- Replacement of 6PPD and Zn, which appears to be imminent in the US, but less so in the EU where an assessment on 6PPD is still ongoing and is allowed up to 0.1%; and
- Exploration of alternatives for other tyre-related compounds such as benzothiazoles, DPG, and MMM in the US; 6PPD (or any amino-substituted diarylamines), 1-octanethiol, aniline, and benzothiazoles in Europe.

INDUSTRY EFFORTS ON TYRE DESIGN

The examples above highlight the significant emphasis manufacturers place on reevaluating raw materials to meet sustainability objectives, while efforts to mitigate tyre wear and address chemicals of concern appear secondary. For instance, the primary goal of the ContiGreen concept is to use more sustainable rubber sources, improve tyre rolling resistance, and reduce CO_2 emissions, and by doing so, indirectly reduce tyre wear. Efforts to address chemicals of concern, which are key in some global regulations (see Section 1), receive less attention on individual manufacturer websites and are mainly featured in large-scale collaborations involving tyre manufacturers but led by larger associations or government entities. For example, the push to find alternatives for 6PPD follows regulations suggesting its potential ban, particularly in the U.S. The USTMA consortium and CRADA are spearheading the search for alternatives, with similar activities occurring across the US (e.g., Washington state[119], Berkeley[120]).

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[119] https://www.ezview.wa.gov/site/alias__1962/37732/research_and_proposed_alternatives_to_6ppd.aspx

[120] https://bcgc.berkeley.edu/greener-solutions-2021-alternatives-6ppd-tire-manufacturing

In contrast, raw material suppliers (chemical suppliers) focus on improving the ozone resistance of the rubber itself rather than directly replacing 6PPD. Meanwhile, such initiatives are not as prominent in Europe. Programs within the Tyre Industry Project[121] (Euro) and the European Tyre and Rubber Manufacturers' Association (ETRMA) focus more on tyre emissions (e.g., TRWP) and recyclability, aligning with European regulations. Discussions about finding alternatives for other tyre-related compounds mentioned in global regulations (e.g., benzothiazoles, DPG, HMMM, etc.) are lacking. Given the current focus on 6PPD, tyre manufacturers may delay research and development on these other chemicals until regulations require it.

RESEARCH INITIATIVES IN TYRE DESIGN

The research conducted at the academic, industry, and consortium levels highlights a broad range of potential changes in tyre design and manufacturing. The use of sustainable materials—such as fillers, polymers, rubber sources, and oils—is at the forefront of much of this research. Significant investments are being made in tyre recycling to create high-value secondary raw materials. However, it remains unclear how these systems can be implemented on a continuous scale, particularly given the significant diversification in tyres. Current processes like pyrolysis or devulcanisation may not be directly applicable to these new materials.

The primary contaminant of concern covered in these research initiatives is 6PPD, likely in response to upcoming regulations and potential bans on this chemical. There is a noticeable lack of organized research programs focusing on other potential contaminants of concern that have been mentioned in many of the current regulations (see Section 2), or these efforts are less publicized and remain within fundamental academic research. This focus may ultimately be driven by governments that implement these policies and regulations and are responsible for protecting human health and the environment from hazardous chemicals. Computer simulations are helping in designing tyres with low wear rates through optimised tread design. Research on silica fillers to improve tyre's resistance to abrasion is also undergoing.

While the extent of progress in these innovations is uncertain, it is evident that closing the loop with new tyres and designs has not yet been fully considered. The focus on sustainability, particularly in raw materials used, appears to sideline efforts on minimising waste and pollution. Achieving circularity and manufacturing truly sustainable tyres by 2050 will require the industry to address this next critical step.

REGIONAL APPROACHES FOR CHEMICALS OF CONCERN

The UK and Canada are notably proactive in their regulatory measures to eliminate chemicals of concern, with frameworks like those in the US and EU (Section 2). New Zealand's strategy leans towards conservatism, prioritizing risk management over elimination, although there seems to be an evolution in the regulation of chemicals. For specific substances, the onus now lies on manufacturers to prove low risk for market approval, departing from traditional prohibition methods. Asian nations, especially Japan and China, display a growing level of proactivity, while India's regulatory landscape is still in the development phase. The influence of political structures seems to play a significant role in shaping the advancement of regulatory frameworks within these regions. In comparison, Australia generally adopts a balanced, science and risk-based approach to regulating chemicals of concern, often leveraging international data and standards. This approach tends to be more passive-reactive, with the level of proactivity dependent on the specific chemical, data availability, and international regulatory trends.

[121] https://www.wbcsd.org/Sector-Projects/Tire-Industry-Project

7 Key insights

TYRE DESIGN CHANGES

Tyre design changes being undertaken by manufacturers can be categorized into structural/physical and compositional/chemical modifications. Structural/physical changes include variations in tread designs, tyre size, thickness, and reinforcements. Compositional/chemical changes involve the type of rubber used (natural, synthetic, recycled), as well as adjustments in fillers and additives such as polymers, silica, recovered carbon black, nanomaterials, and oils. Additionally, changes driven by regulatory requirements, such as replacing likely-to-be banned chemicals like 6PPD, are also expected.

These changes may pose challenges to existing recycling efforts, potentially increasing the complexity of physical separation processes or affecting the quality of recycled products. For example, it is unclear whether tyres with enhanced engineering and reinforcements for improved durability are compatible with current tyre handling systems, which may need modification to accommodate the recycling of these newer tyre types. As manufacturers invest in finding sustainable sources of natural rubber, the EOL tyre market may encounter rubber materials with varying compositions and qualities. Tyres made from rubber sourced from guayule, dandelions, other bio-derived materials, oils from soybeans or sunflowers, or those infused with nanomaterials may differ in properties. These compositional changes may require reconsideration of product pathways for EOL tyres and whether current recycling strategies are still applicable.

CHEMICALS OF CONCERN AND TYRE WEAR

Regarding chemicals of concern, the current focus is on replacing 6PPD and reducing tyre wear. Consequently, future tyres in Australia might differ depending on how 6PPD and tyre wear are addressed.

For 6PPD, various alternatives are being explored through collaborations. Monitoring these projects is advisable as they develop. For instance, the global consortium led by USTMA, involving multiple tyre manufacturers, has listed alternatives for Stage 2 evaluation, including 7PPD, IPPD, 77PPD, CCPD, and specialized graphene. Asahi Kasei Corporation is also working on improving the inherent ozone resistance of rubber while maintaining compatibility with other materials. This approach, which avoids similar chemical additives, is attractive due to its potential to reduce environmental risks from chemical leaching. Conversely, the Molecular Rebar design introduces carbon nanotubes (CNTs), that are recognised to have risk concerns. The progress of these approaches remains to be seen but given the involvement of many manufacturers in the USTMA consortium, it is optimistic to think a similar approach will be taken in replacing 6PPD. From a recycling perspective, direct chemical replacements may cause less disruption and could be perceived positively by the community that are aware of the negative impacts of 6PPD, whereas new rubber materials like CNTs might require separate management. However, replacement with similar PPD compounds should still be subject of additional risk assessment as what is being done in Europe.

To reduce tyre wear, manufacturers employ optimized tread designs, reinforced structures (Kevlar, fibres), and additives such as carbon black and silica. While these approaches are common, the specifics, like tread design and silica used, can vary among manufacturers and may be subject to proprietary formulations leading to significant diversification in materials. Examples include tyres like ENLITEN®, ePrimacy, P-ZERO E, which will likely increase in the market as the popularity of electric/hybrid vehicles increases. In comparison, the changes addressing replacing 6PPD appear to be less imminent. Whilst this replacement is desirable, the process may take some time to ensure that any alternative does not compromise the longevity and durability of tyres. From a recycling perspective, the combined structural/physical and chemical changes in tyre design, especially reinforcements, could present challenges in managing EOL tyres.

For instance, increased silica content that enhances durability and reduces wear could mean resulting tyres will be more challenging to breakdown and require different grinding and devulcanisation techniques. The presence of strong and durable fibres to reinforce tyres may also require more advanced techniques to separate fibres from the rubber matrix.

It is important to note that while the current focus of regulations is on 6PPD and tyre wear, there are other compounds (e.g., benzothiazoles, DPG, and MMM) that are of potential concern and are requiring assessment, yet do not currently face restrictions or bans. Future regulations could prompt replacements or further changes if ongoing research identifies significant risks. Nevertheless, as seen from what tyre manufacturers communicate in their websites, it is likely that such efforts would again be driven by government bodies (just like 6PPD) and less likely initiated by manufacturers.

ADAPTING RECYCLING PROCESSES FOR FUTURE TYRE DESIGNS

As many industries strive for greater sustainability, several programs are investing in tyre recycling research and development. Notable initiatives include the BlackCycle project (EU Horizon 2020) and EVERTYRE initiative (Bridgestone), which aims to produce new tyres from EOL tyres; the Tyre Recycling Foundation, focused on recycling 100% of EOL tyres into circular, sustainable markets like rubber modified asphalt; Enviro's pyrolysis-based technology for recovering high-quality carbon black; and Life Green Vulcan, which seeks to enhance tyre recycling through an environmentally friendly devulcanisation process.

While these programs might address current EOL tyres, it is uncertain how they will adapt to changes in tyre design and the significant diversification of materials. Current recycling methods, such as pyrolysis and devulcanisation, may not be directly applicable to these new materials. Additional considerations are needed to determine how best to integrate these diverse waste streams into current processes. For example, it's unclear whether recovering carbon black through pyrolysis remains viable for tyres with increased silica content, or if existing devulcanisation processes will work with tyres containing Molecular Rebar (CNTs). Additionally, the more complex blend of oils recovered from pyrolysis might require further processing, and rubber-modified asphalt may need to be adjusted for materials derived from tyres made with different natural or synthetic rubbers.

To achieve circularity and truly sustainable tyre manufacturing by 2050, it will be crucial to integrate new tyre designs and materials into developing recycling, recovery, and/or repurposing processes. Whole-of-life analysis is needed for any new tyres developed from new materials or methods to determine how they fit into current EOL market environments.

REGULATORY ALIGNMENT

Aligning with international standards can offer valuable guidance for regulating of chemicals of concern in tyres, as these standards often influence decision-making in Australia. These global standards will need to be adapted to fit the Australian context, balancing international norms and local practicality. Data on chemicals of concern in tyres entering Australia, an understanding of relevant exposure pathways, and assessments of effects on local species are key pieces of information needed to ensure that international standards are relevant and applicable in the local context. It is important to also balance reactive and precautionary regulations to protect human health and the environment, while avoiding undue burdens on industry and maintaining practical feasibility and safety. This balanced approach should consider industry capabilities, economic impacts, and environmental and human health protection.

From an EOL perspective, it is important to evaluate these global regulations when determining pathways for reuse/repurposing tyre products. Potential risks from chemicals other than 6PPD should be recognised and can help shape recycling processes and products to lessen their environmental impact, irrespective of regulatory outcomes.

It is also important to consider the consequences of US restrictions/bans on 6PPD-containing tyres for Australia. These tyres could be redirected to regions with less stringent regulations, including Australia. On the other hand, if Australia imposes similar restrictions, the tyre industry might face higher costs, supply chain disruptions, and reduced competitiveness. However, these challenges must be weighed against the potential environmental and health benefits, and what could be managed.

In summary, staying informed about potential future developments in the tyre manufacturing, research, and regulations can lead to better decisions on recycling technologies and markets for incoming tyres. By implementing a strategy tailored to Australia's specific needs and aligned with international regulations, Australia can enhance its trade and collaboration with other countries, creating new opportunities for Australian recycled tyre products. Whilst aligning with the strictest global standards may prevent Australia from becoming a dumping ground for non-compliant products, it is crucial to assess the potential impact on the tyre industry. Finding the right balance between effectively managing risks and avoiding unnecessary burdens is essential. Collaboration among tyre manufacturers, regulatory agencies, researchers, and organisations like TSA is crucial for generating local data, strengthening future strategies and ensuring a circular economy for all used tyres.

8 Appendix

Table A 1. Chemicals related to tyres and rubber, as taken from the GADSL REFERENCE LIST 2024 Version 1.0. Regulatory status for each chemical is denoted as "D" for declarable, and "P" for prohibited. Reason code, "LR" is used for to those where reporting is required by a regulation, "FA" if it is being assessed by a regulatory agency for possible but not necessarily probably restriction, or "FI" if information is being collected for a non-regulatory purpose.

GADSL #	Substance	CAS RN	Classification	Reason Code	Source (Legal requirements, regulations)	Generic examples
5	Acrylonitrile	107-13-1	D	FI	Reg. (EC) No 1272/2008	Production of plastics, resins and rubbers eg. ABS (residual monomer)
9	Amines, which can form carcinogenic Nitrosamines, selected		D	FI	Legally regulated according to German TRGS 615. Limit for all secondary Amines in volatile corrosion inhibitors, which can form carcinogenic Nitrosamines. Volatile corrosion inhibitors include papers, plastic films and oils.	polyurethane foams, corrosion inhibitors, lubricants, rubber, colourants, herbicides
10	4-Aminobiphenyl and its salts, all members		P	LR	(EC) No 1272/2008, carcinogen class 2 Reg. (EC) No 552/2009 Reg. (EC) No 1907/2006 (REACH)	Impurities in textile and leather paints, antioxidants in lubricants, rubber/latex, plastics
16	Antimonytrioxide (Diantimonytrioxide)	1309-64-4	D	FI	Reg. (EC) No 1272/2008	Flame retardant synergist for plastics and rubber/latex, opacifier, friction material component
17	Aromatic amines, selected		D/P	FI/LR	Reg. (EC) No 1272/2008 Reg. (EC) No 1907/2006 (REACH) Reg. (EU) No 2018/1513 (REACH)	Impurities in textile and leather paints, antioxidants in lubricants, rubber/latex, plastics
26	1,4-Benzenediamine, N,N' - mixed phenyl and tolyl derivs	68953-84-4	D/P	~~FI~~ LR	Canada Gazette Vol. 140, No. 49 - December 9, 2006 (Canadian Challenge). The Canadian Challenge is regulated under the Part 5, Section 71, of the Canadian Environmental Protection Act, 1999 (CEPA, 1999). Japan Chemical Substances Control Law [Class1] (Only ditolyl form is prohibited. Diphenyl or phenyltolyl form is not prohibited)	Rubber tires; elastomers in butyl rubber; anti-aging agent; sealants

27	1,4-Benzenediamine, N,N'-mixed Ph and tolyl and xylyl derivs.	68953-83-3	D	FI	Included in list of substances under REACH PACT assessment	Anti-degrading agent in rubber
29	1,2-Benzenedicarboxylic acid, dihexyl ester, branched and linear	68515-50-4	D/P	LR	Reg. (EC) No 1907/2006 (REACH Annex XIV)	Plasticiser in rubber
38	Benzidine and its salts, all members		P	LR	Reg. (EC) No 1272/2008, carcinogen class 2 Reg. (EC) No 552/2009 Reg. (EC) No 1907/2006 (REACH) Canadain Toxic Substances Regulation 2005	Impurities in textile and leather paints, antioxidants in lubricants, rubber/latex, plastics
44	2-Benzothiazolesulphenamide, N, N-dicyclohexyl-	4979-32-2	D	FI	Japan Chemical Substances Control Law [Monitoring]	Vulcanisation accelerator for tires and rubber products
	Allyl isothiocyanate	57-06-7	D	LR	Approval of biocide needed for product-type 7 Approval of biocide needed for product-type 8 Approval of biocide needed for product-type 9	Fibre, leather, rubber and polymerised materials preservatives
54	Bis(chloromethyl) ether (BCME)	542-88-1	P	LR	Prohibition of Certain Toxic Substances Regulations, 2005 (SOR/SOR/2005-41. Published in Canada Gazette Part II, 2006-11-29 Vol. 140, No. 24 K-REACH	Surface treatment of vulcanised rubber to increase adhesion, and in the manufacture of flame-retardant fabrics (ATSDR 1989).
59	Butadiene, 1,3 -	106-99-0	D	FI	Reg. (EC) No 1272/2008	Manufacturing of synthetic rubber for tyres, as homopolymerisate (BR), as copolymerisate with Styrene (SBR) or Acrylonitrile (NR), starting product of Sulfolane, Chloroprene, Hexadiamine, softeners, Tetrahydrophthalic acid anhydride, residual monomer in ABS
61	Chlorinated hydrocarbons, selected		D/P	FI/LR	Multiple (see below). Several chlorinated hydrocarbons listed are not explicitly prohibited in applications associated with manufactured articles, however, within the EU there is a general regulatory presumption toward substitution for industrial uses.	Solvent and other dispersive applications. Also includes manufacturing process uses resulting in impurities associated with leather, foams, paints, rubbers, and adhesives applications.

	Alkanes, C_{10-13}, chloro	85535-84-8	P	LR		Flame retardants in rubbers and textiles, paints and coatings, etc., extreme pressure additives in metal working fluids.
	Alkanes, C_{12-13}, chloro	71011-12-6	P	LR		Flame retardants in rubbers and textiles, paints and coatings, etc., extreme pressure additives in metal working fluids.
	Alkanes, C_{14-17}, chloro	85535-85-9	D	LR		Secondary plasticisers in polyvinyl chloride (PVC), extreme pressure additives in metal working fluids, plasticisers in paints, additives to adhesives and sealants, in fat liquors used in leather processing, flame retardant plasticisers in rubbers and oth
	Paraffin oils, chloro	85422-92-0	D/P	LR		often in rubbers
79	Diazene-1,2-dicarboxamide, Azodicarbonamide (ADCA)	123-77-3	D	LR	Reg. (EC) No 1907/2006 (REACH Candidate List)	Blowing agent used for plastics, rubber, adhesive and sealants.
81	1,3-diethyl-2-thiourea	105-55-5	D	FA	Included in ECHA Regulatory needs assessment where Restriction is recommended	Reported in rubber materials including EPDM and NBR, and in adhesives.
82	1,3-dihydro-4(or 5)-methyl-2H-benzimidazole-2-thione	53988-10-6	D	FI	Included in list of substances under REACH PACT assessment	Tyres
83	1,3-dihydro-4(or 5)-methyl-2H-benzimidazole-2-thione, zinc salt	61617-00-3	D	FI	Included in list of substances under REACH PACT assessment	Tyres
87	N-1,3-dimethylbutyl-N'-phenyl-p-phenylenediamine, (6PPD)	793-24-8	D	FA/LR	May 2023 SAFER CONSUMER PRODUCTS REGULATIONS – Listing Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD) as a Priority Product Department of Toxic Substances Control reference number: R-2022-04R California Code of Regulations: title 22, division 4.5, chapter 55, article 11, section 69511.7	Tires
97	6,6'-di-tert-butyl-2,2'-methylenedi-p-cresol	119-47-1	D	LR	Reg. (EC) No 1907/2006 (REACH Candidate List)	Additive in adhesive materials; additive in NR, NBR, EPDM rubbers.

98	6,6'-di-tert-butyl-4,4'-thiodi-m-cresol	96-69-5	D	FI	Included in list of substances under REACH PACT assessment Included in list of substances under assessment in phase 3 of Canadian Chemical Management Plan (CMP3) (2016-2020)	Elastomers / elastomeric compounds, Sealing Rubber,
101	Dodecachloropentacyclo 1, 3, 4-Metheno-1H-cyclobuta(cd)pentalene, Mirex	2385-85-5	P	LR	Prohibition of Certain Toxic Substances Regulations, 2005 (SOR/SOR/2005-41. Published in Canada Gazette Part II, 2006-11-29 Vol. 140, No. 24	Flame retardant in plastics, rubber, paint, paper, and electrical goods from 1959 to 1972. Mirex was sold as a flame retardant under the trade name Dechlorane, and chlordecone was also known as Kepone.
103	Dodecamethylcyclohexasiloxane (D6)	540-97-6	D	LR	Reg. (EC) No 1907/2006 (REACH Candidate List)	Intermediate chemical, remains in the final product of varying content. Use for silicone rubbers, adhesives, sealants, coatings... As well as lacquers, polishes, waxes, washing & cleaning products
115	Ethyelenethiourea/Imidazolidine-2-thione	96-45-7	D	LR	Reg. (EC) No1907/2006 (REACH Candidate List)	Vulcanisation agent for rubber products
119	Hexachlorobenzene	118-74-1	D/P	~~FI/~~LR	Reg. (EU) 2019/1021, (EC) No 1272/2008 The Canadian Prohibition of Certain Toxic Substances Regulations 2012 Regulation states at Section 4 that: ...a person must not manufacture, use, sell, offer for sale or import a toxic substance set out in schedule 1 or a product containing it unless the toxic substance is incidentally present. Japan Chemical Substance Control Law [Class I]. Must use BAT (Best Available Technology) to assure lowest concentration. Levels above BAT are prohibited see https://www.meti.go.jp/policy/chemical_management/english/files/laws/byproduct_class1.pdf South Korea Enforcement Rule of the Persistent Organic Pollutants Control Act	As a peptizing agent in the production of nitroso compounds and rubber for tires. As impurities in colorants
120	Hexachloro-1,3-butadiene (HCBD)	87-68-3	P	LR	Prohibition of Certain Toxic Substances Regulations, 2005 (SOR/SOR/2005-41. Published in Canada Gazette Part II, 2006-11-29 Vol. 140, No. 24	Used mainly as an intermediate in the manufacture of rubber compounds. It is also used in the production of lubricants

152	2-Naphthylamine and its salts, all members		P	LR	Reg. (EC) No 1272/2008, carcinogen class 1A Reg. (EC) No 552/2009	Impurities in textile and leather paints, antioxidants in lubricants, rubber/latex, plastics
155	Nitrites, all members		D/P	FI/LR	Reg. (EC) No 1272/2008	Additives in engine coolants, vulcanising agents in rubber products, anticorrosion surface additive. Reaction product precursor for potentially carcinogenic N-nitroso- compounds
156	4-Nitrobiphenyl and its salts, all members		P	LR	Reg. (EC) No 1272/2008, carcinogen class 2 Reg. (EC) No 552/2009	Impurities in textile and leather paints, antioxidants in lubricants, rubber/latex, plastics
	N-Nitroso diethanol amine	1116-54-7	D	FA		Rubbers (including synthetic rubbers); reaction and cleavage products from the polymerization system
	Dimethylnitrosoamine; N-nitrosodimethylamine Methanamine, N-methyl-N-nitroso-	62-75-9	P	FA	Prohibition of Certain Toxic Substances Regulations, 2005 (SOR/SOR/2005-41. Published in Canada Gazette Part II, 2006-11-29 Vol. 140, No. 25	Major releases of NDMA have been from the manufacture of pesticides, rubber tires, alkylamines, and dyes.
164	Octamethylcyclotetrasiloxane	556-67-2	D	LR	Reg. (EC) No 1907/2006 (REACH Candidate List)	Softener, elastomers, rubber
166	Oligomerisation and alkylation reaction products of 2-phenylpropene and phenol		D	FI	Included in list of substances under REACH PACT assessment	Additive for rubber
167	4,4'-oxydianiline	101-80-4	D	LR	Reg. (EC) No 1907/2006 (REACH Candidate List)	Heat resistant agent for ACM rubber
195	Phenol, 2-(2H-benzotriazol-2-yl)-4-(1,1-dimethylethyl)-6-(1-methylpropyl)- (UV 350)	36437-37-3	D/P	LR	Reg. (EC) No 1907/2006 (REACH Annex XIV)	UV-protection agents in coatings, plastics, rubber
197	Phenol, 4-methyl-, reaction products with dicyclopentadiene and isobutylene	68610-51-5	D	FI	Included in list of substances under REACH PACT assessment	rubber, adhesives, sealants, elastomers, duromers

225	Polycyclic aromatic hydrocarbons (PAH; PCAH), selected		D/P	FI/FA/LR	Reg. (EC) No 1907/2006 (REACH) Reg. (EC) No 552/2009; Reg. (EC) No 1272/2008; General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ)of the People's Republic of China Reg.(EU) No 2018/1513 (REACH)	Extender oils and extender oils in tyres; Polymers, rubber articles in contact with skin
227	2-Propanone, reaction products with diphenylamine (PREPOD)	68412-48-6	D	FI	October 15, 2011 the Canadian government declared PREPOD as Toxic. They are proposing to ban the use of this substance.	additive in rubber parts, paint additive, plasticizer
235	Quinoline	91-22-5	D	FA	ARN Restriction. Substance included in Assessment of Regulatory needs where Restriction concluded as next regulatory step.	Rubber materails used in hoses and seals. NBR rubber, PET and grease / lubricant. ECHA uses include use as an intermediate / monomer, and automotive care products, paints and coatings
268	Thioperoxydicarbonic diamide ([(H2N)C(S)]2S2), tetramethyl-; Thiram; Tetramethylthiuram disulphide;	137-26-8	D/P	FI/LR	Japan Waste Management and Public Cleansing Law Reg. (EU) No 528/2012 See GADSL Reference Biocide	Vulcanisation accelerator for rubber

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