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USED TIRE ECOSYSTEM FOR THE RECLAIMED RUBBER INDUSTRY DEVELOPMENT AT PT BRIDGESTONE TIRE INDONESIA

EKOSISTEM BAN BEKAS UNTUK PENGEMBANGAN INDUSTRI KARET REKLAMASI (RECLAIMED RUBBER) DI PT BRIDGESTONE TIRE INDONESIA

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ABSTRAK

Pengelolaan limbah ban bekas menjadi isu global yang mendesak karena karakteristik ban sulit terurai secara alami dan memerlukan waktu lebih dari 50 tahun untuk proses dekomposisi. Di wilayah Jabodetabek (Jakarta, Bogor, Depok, Tangerang, Bekasi), timbulan ban bekas diperkirakan mencapai 2,5–3 juta unit per tahun, dengan kontribusi terbesar berasal dari Karawang (1.000 unit per bulan) dan Bogor (820 unit per bulan). Limbah ban bias bekas mengandung hingga 70% karet, memiliki potensi besar untuk didaur ulang menjadi bahan baku untuk ban baru melalui teknologi karet reklamasi (reclaimed rubber), sejalan dengan prinsip ekonomi sirkular. Penelitian ini bertujuan untuk memetakan ekosistem rantai pasok ban bekas, mengidentifikasi aktor utama, dan mengoptimalkan aliran bahan baku untuk mendukung pengembangan industri karet reklamasi. Metode yang digunakan adalah metode deskriptif kualitatif. Penentuan jumlah lokasi penelitian dilakukan menggunakan metode Solvin dengan tingkat toleransi atau error 25% dan observasi dilaksanakan pada 15 toko ban spesifik, dua toko ban truk, tiga fleet, dan tiga pengepul ban bekas yang berada di wilayah Jabodetabek dan Jawa Barat. Hasil penelitian menunjukkan bahwa total estimasi ban bekas yang terkumpul di Jabodetabek dari toko ban spesifik, toko ban truk, fleet end user, dan pengepul mencapai 2.860 unit per bulan. Tantangan utama dalam pengelolaan ban bekas adalah keterbatasan fasilitas penyimpanan, rendahnya kesadaran akan nilai ekonomi limbah, serta sistem pengelolaan yang masih bersifat konvensional. Penelitian ini juga menunjukkan bahwa selama ini hanya 20% limbah ban yang dapat dimanfaatkan secara optimal, menunjukkan potensi besar yang belum terkelola dengan baik.

Kata kunci: ban bekas, karet reklim, rantai pasok, ekonomi sirkular

ABSTRACT

Managing end-of-life tyres (ELTs) has become an urgent global issue because tyres are difficult to decompose naturally and take more than 50 years to break down. In the Jabodetabek (Jakarta, Bogor, Depok, Tangerang, Bekasi) area, ELT generation is estimated at 2.5–3 million units annually, with the most significant contributions from Karawang (1,000 units per month) and Bogor (820 units per month). Bias-ply used tires, which contain up to 70% rubber, have significant potential for recycling into raw materials for new tires through reclaimed rubber technology, aligning with the principles of a circular economy. This study aims to map the supply chain ecosystem of ELTs, identify key stakeholders, and optimise material flow to support the development of the rubber industry from reclaimed materials. The study employs a qualitative descriptive method. The number of research locations was determined using the Solvin method with an error rate of 25%. Observations were performed at 15 specific tire shops, two truck tire shops, three fleets, and three used tire collectors in the Jabodetabek and West Java areas. The findings indicate that the total estimated number of ELTs collected in Jabodetabek from tire stores, truck tires, fleets, and collectors reaches 2,860 monthly units. The main challenges in ELT management include limited storage facilities, low awareness of the economic value of waste, and a predominantly conventional management system. The study also reveals that only 20% of ELTs are utilised optimally, highlighting a significant untapped potential.

Keywords: used tires, reclaimed rubber, supply chain, circular economy

**Coressponding Author*

INTRODUCTION

Waste from used tires, also known as end-of-life tires, has recently become a pressing issue in society and has emerged as a global concern that requires increasingly urgent attention. Globally, it is estimated that more than 1.5 billion used tires containing over 40% vulcanised rubber are discarded yearly (Bockstal *et al.*, 2019; Fazli and Rodrigue, 2020). According to data from the World Business Council for Sustainable Development (2019), global tire production reaches 1.4 billion units annually, with approximately 1 billion tires reaching the end of their service life. Of those end-of-life tires, only about 50% are successfully and efficiently recycled, while the remainder are either discarded or incinerated, resulting in significant environmental problems.

Indonesia, with over 150 million motor vehicles as of 2023 (BPS, 2023), faces an increasingly complex issue regarding the disposal of used tires. Based on this data, the problem of end-of-life tires is expected to intensify. The amount of used tire waste in Indonesia continues to rise in line with the growing number of vehicles, directly correlating with the annual increase in tire production (Mukti, 2022; Dwianto, 2023). According to the Indonesian Tire Manufacturers Association (APBI), in 2022, Indonesia produced 58.6 million tires, which is projected to increase by 10.7% in the following year, with an estimated 11–12 million units of used tire waste annually. However, only 20% of this waste is optimally utilised, indicating a significant potential that remains underexploited.

Used tires are a common form of non-biodegradable solid polymer-based waste (Zerin *et al.*, 2024). Bias-ply tires, or fabric-ply tires, contain up to 70% rubber, making them recyclable into high-value reclaimed rubber products. The complex structure of tires and their natural decomposition period, which exceeds 50 years, underscores the importance of properly managing used tires (Supriyanto *et al.*, 2017; Falaah and Cifriadi, 2018; Xiao *et al.*, 2022). This is reflected in the global market value of reclaimed rubber, which reached USD 6.32 billion in 2021, highlighting the significant economic potential in waste tire processing.

The Greater areas (Jabodetabek: Jakarta, Bogor, Depok, Tangerang, Bekasi), with a population of approximately 32 million and around 20 million motor vehicles, generate an estimated 2.5–3 million units of used tire waste annually. This region features several used tire collection centres strategically located in industrial zones, including MM2100 Industrial Area in Bekasi, Jatake Industrial Area in Tangerang, and Ancol Industrial Area in North Jakarta. According to the Jakarta Environmental Agency (2023), implementing a circular economy approach to used tire management in this region can create 12,000 new jobs and reduce CO_2 emissions by 450,000 tons annually. The World Economic Forum (2022) also reported that producing one new tire requires approximately 7 gallons of petroleum, whereas producing comparable-quality reclaimed rubber products requires only 2.5 gallons of oil. Geissdoerfer *et al.* (2022) found that implementing a circular economy model in the tire industry can reduce the carbon footprint by up to 85% compared to conventional production methods.

Based on the above, these conditions present opportunities and challenges for developing the reclaimed rubber industry. PT Bridgestone Tire Indonesia, one of the leading tire manufacturers in the country, has a vision that aligns with the current opportunities and challenges in processing used tires. The company focuses on high-quality tire production and is firmly committed to social and environmental responsibility. PT Bridgestone Tire Indonesia aims to utilise 40% recycled and renewable materials by 2030 and 100% sustainable materials by 2050. This commitment aligns with its corporate mission, "To help ensure a healthy environment for current and future generations", and its dedication to the Bridgestone E8 Commitment, positioning the company as an active player in the transition toward a circular economy. Comprehensive research aims to map the used tire supply chain ecosystem, identify key actors, and optimise the flow of raw materials to support the development of the reclaimed rubber industry. With this approach, innovative solutions can be found that strengthen the circular economy and support environmental sustainability.

MATERIAL AND METHODS

The research employed a qualitative descriptive method. Data collection was conducted through literature review and field studies. The literature review involved gathering journals and reference books discussing the used tire supply chain, emerging issues, and the processing of reclaimed rubber. The field study was conducted through interviews and direct observations to collect relevant data, including the used tire supply chain, the actors involved, current used tire management practices, and the potential of used tires as a raw material.

Field observations were conducted from September to November 2024. The number of survey locations was determined using the Slovin formula, which is designed to calculate the minimum required sample size from a known population (Maimunah *et al.*, 2020). This study applied a margin of error of 25%, considering the high heterogeneity in the distribution of tire shop locations across the Greater Jakarta (Jabodetabek) and West Java area. The sample size calculation using the Slovin formula is presented in Equation (1).

$$n = \frac{N}{1+N\ x\ e^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(Equation 1)}$$

Where:

n : Number of samples (sample size)

N : Total population
e : Margin of error (tolerance level)

Based on the calculation using the Slovin formula with a population size (N) of 144 and a margin of error (e) of 0.25, the minimum required sample size (n) was determined to be 14.4. Considering the practicality of implementation and the need for adequate data representation, the sample size was rounded to 15 specific tire retail outlets, deemed sufficient to represent the overall population in the Jabodetabek and West Java areas. The selection of these specific outlets was conducted purposively by the management of PT Bridgestone Tire Indonesia. The number of samples determined using the proportional sampling method includes two truck tire centres, three fleets, and three used tire collectors.

Ta'ani *et al.* (2024) explained that each region within the Greater Jakarta area (Jabodetabek) has varying levels of population density, which directly influence the economic benefits across these regions. Population density changes affect the number of potential customers and shape the competitive dynamics and business strategies adopted by tire shops in each area (Hikmawati and Nuryakin, 2017). The selected 25% margin of error provides sufficient flexibility to capture these variations without requiring a considerable sample size.

RESULT AND DISCUSSION

Estimated Availability of Used Tires

Specific tire shops are retail units across Indonesia collaborating with PT Bridgestone Tire Indonesia to market and distribute its tire products. These shops sell radial tires for small passenger vehicles and bias-ply (fabric) tires for larger vehicles such as trucks and buses. This study is based on a sample of 15 specific tire shops and two truck tire shops located in the Jabodetabek and West Java area. Several tire shops have directly partnered with fleet operators, including logistics and commercial vehicle service providers.

Truck tire shops are outlets under the distribution network of PT Bridgestone Tire Indonesia. These shops specialise in selling commercial tires for trucks, buses, and large loaders. A formal distribution agreement must be made with PT Bridgestone Tire Indonesia to establish a truck tire shop. General tire shops offer tires, including new tires from multiple brands and usable, second-hand tires sold directly to end consumers. Fleets refer to tire consumers, such as logistics companies or commercial vehicle operators, that purchase new tires from either tire shops or authorised distributors for use in their operational vehicles. Collectors are key actors in the collection and distribution of used tires. They typically travel between specific tire shops, general tire shops, fleets, and truck tire shops to purchase and retrieve used tires. The collected tires are then sorted by quality and forwarded to the following actors in the supply chain. An estimated 1,100 new tires are used monthly by specific tire shops, truck tire shops, fleets, and collectors, as illustrated in Figure 1.

The sales and usage of 1,100-size new tires amount to approximately 2,320 monthly units. These tires, primarily used for trucks and buses, are distributed as follows: 400 units are sold by specific tire shops, truck tire shops sell 1,300 units, and fleets use 620 units as end users. The estimated potential of the 1,100-size tires, distributed across 15 specific tire shops, two truck tire shops, four fleets, and two collectors, reaches 2,860 monthly units. The availability of used tires at specific and truck tire shops is relatively low, as used tires require significant storage space. This limitation makes shop owners less inclined to store used tires. The recorded used tires represent those kept temporarily in shops before being collected by aggregators.

Used truck and bus tires, specifically bias-ply tires, have a higher economic value than radial-type used tires due to their broader range of reuse applications. As a result, many users retrieve their used tires after replacement at tire shops. Truck tire shops often implement a rim delivery system to fleets that have established partnerships with them, allowing the collection and management of used tires to be handled directly by the fleets. The Sunter truck tire shop records the highest number of collected used tires among all observed specific and truck tire shops. This is attributed to its high sales volume and many fleet partners associated with the shop. Some fleets replace their tires and leave the used ones at the location where they are replaced. However, the used tires collected at fleet locations are typically severely damaged and unsuitable for retreading. On average, fleets collaborate with retreading businesses as a cost-saving measure. The estimated number of 1,100-size used tires collected monthly across specific tire shops, truck tire shops, fleets, and collectors is presented in Figure 2.

It is estimated that Karawang used tire collector stores collect around 1,000 units per month, accounting for 35% of the total 2,860 used 1,100-size tires collected. Companies, including specific tire shops and truck tire shops, generate these used tires. They are sent to a collector in Karawang for further processing. In total, there are seven truck tire shops distributed across Jabodetabek and its surrounding areas. Based on the current average used tire availability observed at two truck tire shops, the estimated availability from all seven shops is approximately 2,100 monthly units.

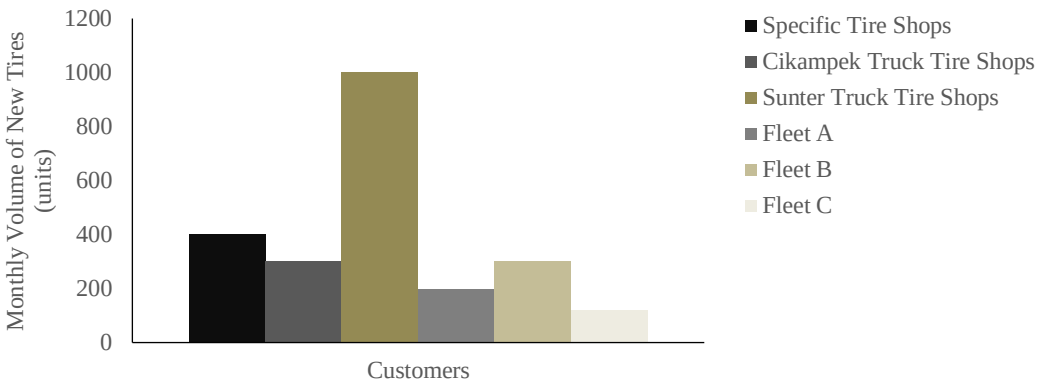

Figure 1. Estimated monthly usage of 1,100-size new tires in specific tire shops, truck tire shops, and fleets

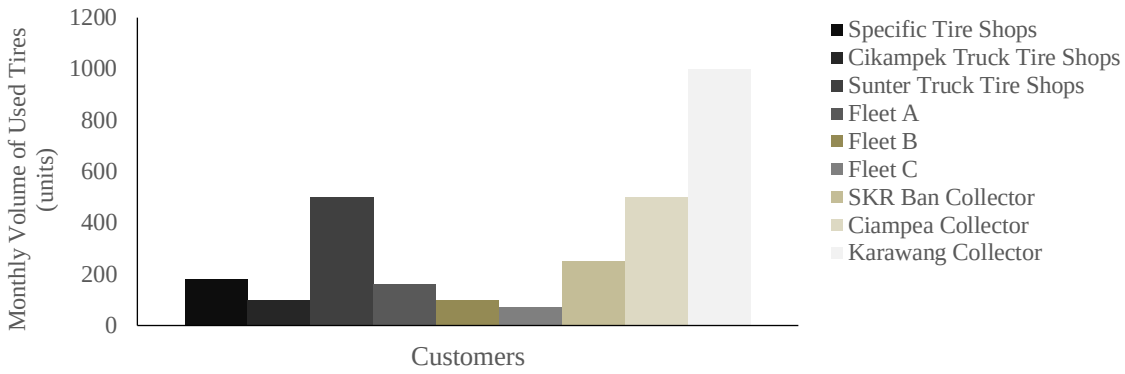

Figure 2. Estimated monthly collection of 1,100-size used tires in tire shops, truck tire shops, fleets, and collectors

The Ciampea collector also gathers around 500 large-sized truck and bus tires per month, as a hub for other roaming collectors who travel around gathering used tires. Collection activities in Ciampea typically operate 6–8 vehicles daily, working from morning to evening. Meanwhile, the Citeureup collector is one of the few that can process damaged tires for reuse using partial retreading techniques, such as blocking or applying raw rubber patches. Additionally, this collector collaborates with cement companies by supplying used tires as fuel for their cement kilns. It also distributes tires to various artisans in the Bogor area who specialise in recycling used tires.

Distribution of 1,100-Size Used Tires by City (Jakarta, Bogor, Tangerang, Karawang, Cikampek)

Karawang is a significant hub for collecting used tires across the Jabodetabek region, particularly for truck and bus tire types. On average, around 1,000 units are collected per month in this area. This figure is followed by Bogor, with approximately 820 units per month. Karawang's high potential is closely tied to its status as one of Indonesia's most significant industrial zones, with an industrial area spanning 36,757 hectares (Rahmawati and Nurwati, 2021) and housing 10,569 industrial units spread throughout the region (Akbar, 2023). This industry concentration drives high volumes of heavy-vehicle traffic, which generates a substantial amount of used tire waste.

Bogor also plays a significant role in used tire collection, supported by numerous collectors who gather tires from the city and the surrounding regions. The presence of Fleet C, which serves as an end-user of used tires, further establishes Bogor as a hub for both the distribution and utilisation of used tires. A map illustrating the distribution of 1,100-size used tires by city is presented in Figure 3.

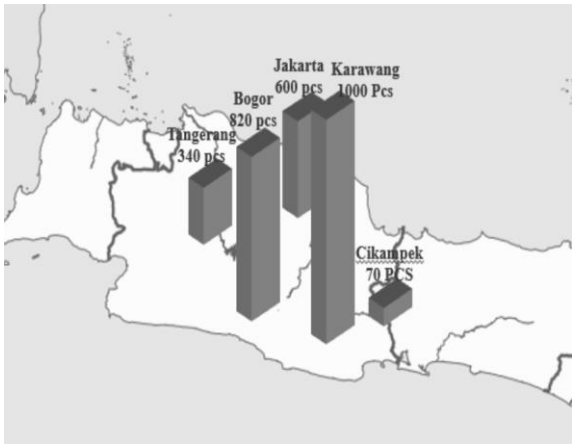

Figure 3. Monthly distribution of 1,100-size used tires by city

Storage Facilities and Retention Period of Used Tires in Warehouses

Warehouses are a critical component in industrial operations, playing a significant role in determining the final quality of products. According to Fadhillah (2022), a warehouse is a storage facility for various types of products, whether in large or small quantities, for a specified period. Products are stored from when the manufacturer produces them until customers or workstations need them within the production facility. In industrial settings, warehouses play a crucial role in supporting production processes, as they influence production quantity and timing, affecting operations' efficiency and effectiveness (Gunawan, 2013).

Used tire warehouses function as temporary storage facilities with varying capacities. On average, the storage capacity for used tires at regular tire shops is approximately 616 units, while truck tire shops can store up to 800 units on average. Interview results indicate that up to 60% of warehouse capacity is typically utilised, with the potential to increase to 80% during significant holiday periods, such as Eid al-Fitr.

The accumulation of used tires in storage areas presents new challenges for shop owners, including disruptions to operational mobility and potential health hazards, particularly as a breeding ground for mosquitoes. Interview findings revealed that 11 out of 19 specific and truck tire shops lack dedicated storage for used tires. This is primarily because constructing a separate storage facility requires additional space and costs, prompting many shop owners to transfer used tires directly to collectors.

Warehouse management practices remain conventional, categorising tires by size and condition. This system contributes to inefficiencies in managing used tires, mainly due to limited facilities and storage space. In many cases, new tire inventory, service equipment, and parking areas already occupy the available space, making it challenging to allocate additional space for used tires. Moreover, the perception of store owners and managers influences this issue. Many respondents view used tires as waste with little to no value, causing their management to become a low priority. Interviews also revealed that collectors are willing to purchase used tires from shops—both damaged and reusable ones—at varying prices depending on their condition and type.

Most specific and truck tire shops do not have permanent warehouses but instead provide temporary storage spaces with varying conditions. Five shops use open-air spaces without roofing, three use open-air spaces with roofing, and another three directly deliver used tires to collectors daily, eliminating the need for a warehouse or temporary storage. This approach is considered more efficient as it helps reduce operational costs associated with warehouse management. An adequately sized facility for specific tire shops is approximately 12 m², which can accommodate 200–250 used tires when arranged using a six-tire stacking method. Truck tire shops require different dimensions due to the larger diameter of truck and bus tires, which range from 750 mm to 1200 mm, and the higher quantity of tires handled. For truck tire shops, a warehouse area of 45 m², including a 20% allowance, is considered sufficient to store 300–350 tires using the same six-tire stacking method.

In contrast, insufficient storage space is commonly reported to be around 10 m² for specific tire shops and 30 m² for truck tire shops. These limited dimensions result in low storage capacity, necessitating more frequent transportation of used tires out of the facility. Alternative storage designs for used tires are presented in Figure 4, while examples of current storage conditions are shown in Figure 5.

The characteristics of used tire storage facilities differ significantly from those of new tire warehouses, particularly regarding supporting infrastructure and handling procedures. Interview findings with all respondents indicated that new tire warehouses must have storage racks and enclosed rooms with temperature control maintained at room temperature. In contrast, used tire warehouses do not require racks or enclosed, temperature-controlled spaces; instead, their design focuses on preventing tire piles from becoming breeding grounds for mosquitoes.

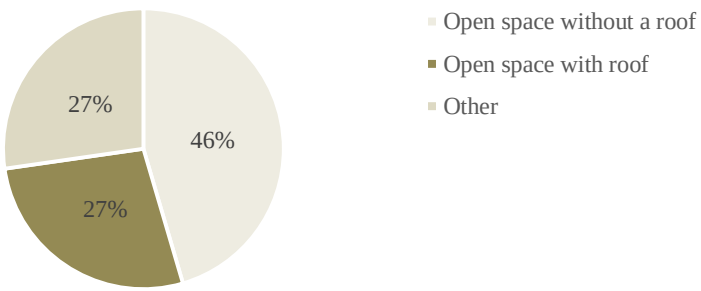

Figure 4. Alternative storage methods for used tires

Figure 5. Used tire storage facilities

According to *Sari et al.* (2023), used tires are among the most favourable breeding sites for Aedes mosquitoes due to their higher humidity than the surrounding environment. The storage duration of used tires in warehouses or temporary storage areas within specific truck tire shops varies. Several factors influence these differences, including warehouse capacity, partnerships with collectors, and demand for used tires. Storage facilities in specific and truck tire shops are generally designed to accommodate short-term storage, with a sufficient capacity for only a few days. On average, used tires are stored for 7 to 9 days in specific warehouses, while in truck tire shops, the storage period is typically 3 to 4 days. This practice aligns with the original design objective of these warehouses: to prioritise operational efficiency and ensure rapid waste management.

Used Tire Management Practices

Used tire management begins at the retail level, including specific, general, and truck tire shops. At this level, two leading management practices are implemented: 1) selling used tires to collectors and 2) paying collectors to pick up used tires. Based on interview results and field observations, 88.2% of retail actors sell their used tires to roaming collectors who collect discarded tires from shop to shop.

The selling price of used tires at the retail level varies considerably based on their condition and type. For passenger car tires, those torn or damaged are typically sold for approximately IDR 5,000 to IDR 10,000, whereas severely deteriorated ones may only be valued at around IDR 1,000. In contrast, second-hand tires are still in usable condition and can be sold for between IDR 50,000 and IDR 100,000, depending on the type of tire. Used tires for trucks and buses also display a broad price range. Heavily worn-out units are generally priced between IDR 5,000 and IDR 15,000, while those suitable for retreading may reach up to IDR 300,000, reflecting their more excellent residual value.

Proceeds from used tire sales at the retail level are commonly redistributed to employees as a form of income bonus. Meanwhile, 11.8% of other retail actors choose to pay collectors to remove the used tires accumulated in their shops. These retailers are typically charged IDR 350,000 per truckload each time a collection is made. The type of vehicle used for transporting used tires from specific tire shops is usually a Colt Diesel Engkel (CDE) truck, with a load capacity of 2–3 tons and a volume capacity of 4–6 cubic meters. This truck can carry approximately 71–106 passenger car tires or 17–25 truck tires per trip.

Used tire management is conducted through a Business-to-Business (B2B) sales model at the collector level. B2B transactions occur when collectors sell accumulated used tires to downstream businesses engaged in tire processing or recycling, such as retreading factories, lime kilns, pyrolysis plants, tire-crafting industries, and automotive workshops. The primary focus of supply chain management at this stage is to ensure the availability of used tires, supported by efficient inventory control and timely distribution.

Used tires are reused in two main ways: 1) as raw materials for processing into derivative or recycled tire products, and 2) as fuel for energy in producing other goods. Used tires that are still in usable condition, though not perfect, are often repaired and restored through retreading or regrooving processes. If the tire is deemed suitable for continued use, automotive workshops may resell it to end users. On the other hand, unusable or severely damaged tires are typically repurposed as alternative fuel sources in industrial production processes, such as cement manufacturing, steel production, and asphalt processing.

Structure of the Used Tire Ecosystem Network

The used tire ecosystem consists of a network structure involving various stakeholders, including PT Bridgestone Tire Indonesia, distributors, specific tire shops, truck tire shops, general tire shops, fleets, consumers, used tire collectors, retread tire factories, lime kilns, used tire suppliers, pyrolysis plants, used tire artisans, tire decorators, automotive workshops, cement factories, steel plants, asphalt plants, car rental companies, reclaimed rubber processors, and Integrated Waste Processing Sites (TPST). The supply chain flow in this ecosystem includes the movement of new tires, used tires, and processed tire products. The structure of this network and the flow pattern of the used tire ecosystem are illustrated in Figure 6.

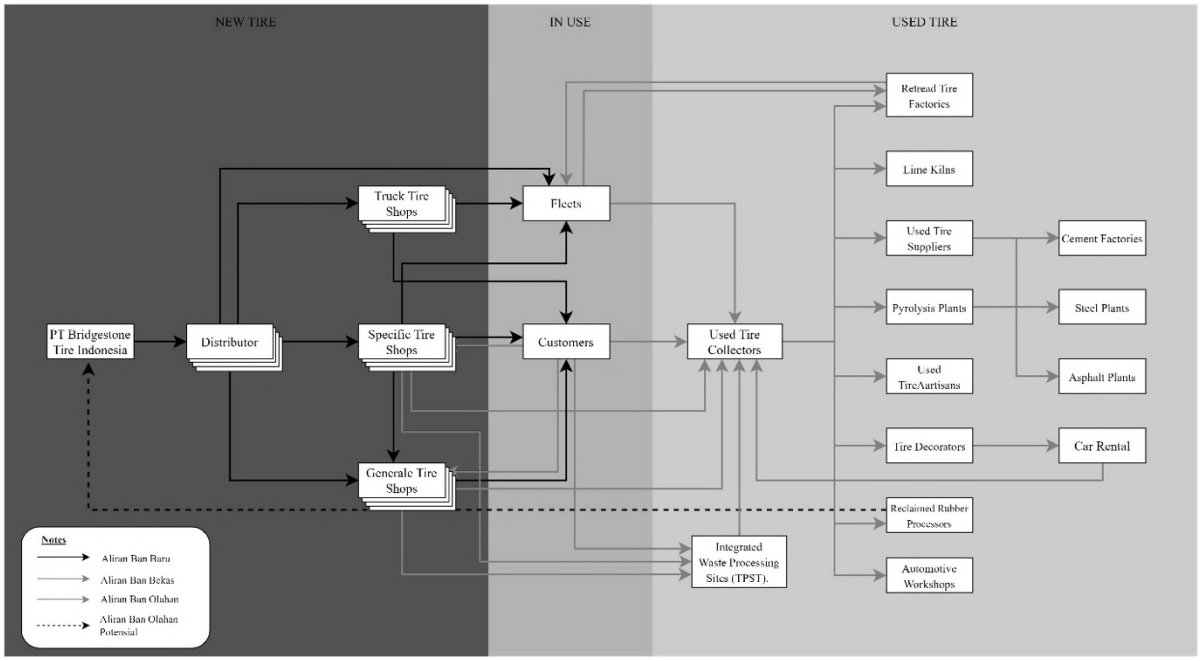

Figure 6. Flow pattern of used tires in the tire ecosystem

The tire flow begins with PT Bridgestone Tire Indonesia, the tire manufacturer. PT Bridgestone Tire Indonesia distributes its products to distributors, who act as intermediaries between the manufacturer and retail stores. They also establish partnerships with large fleet operators to supply tires in bulk. Retail stores within this ecosystem include specialised tire shops, truck tire shops, and general tire shops, which sell tire products to both fleet operators and individual consumers. After being replaced by general consumers, some used tires are left at the shop where the replacement took place. In contrast, others are collected by roaming tire collectors or discarded by consumers. Used tires deemed still usable after fleet usage are sent for retreading at vulcanisation plants.

Tires eligible for retreading have not yet reached the tire wear indicator threshold, which typically indicates about 30% remaining tread depth. These retread tires are then returned to fleet operators for reuse in their operations. Used tires that are no longer suitable for use are passed on to tire collectors for reuse. The collected tires are then distributed to various processors, including retreading factories, lime kilns, used tire suppliers, pyrolysis plants, tire artisans, and tire decorators. Used tires processed by suppliers and pyrolysis plants are further distributed to steel plants, where the metal content is extracted. Tires sent to cement factories are used as an alternative fuel, while those sent to asphalt plants serve as a blending material in asphalt production.

Using reclaimed rubber as a raw material for tire production has contributed to a growing global awareness of the importance of sustainability and resource efficiency. The circular economy approach presents an innovative solution to the waste problem (Yulistika *et al.*, 2023), particularly in the context of the increasing volume of used tire waste.

This approach offers an eco-friendly alternative, reducing dependency on natural and synthetic rubber, which rely on exploiting finite natural resources. With an estimated 2,860 used tires generated per month, there is significant potential for processing these into reclaimed rubber. However, current calculations indicate that the cost of goods manufactured (COGM) for laboratory-scale reclaimed rubber remains high, at approximately IDR 107,704 per kilogram, substantially exceeding the market price used by PT Bridgestone Tire Indonesia.

To achieve a more competitive price, several efficiency strategies must be adopted. These include optimising material composition, adjusting raw material pricing to reflect larger-scale production, and enhancing supply chain efficiency. Additionally, technological advancements in production processes are crucial in reducing overall costs. Given the increasing stringency of environmental regulations and industrial targets, such as Bridgestone Indonesia's commitment to using 40% recycled materials by 2030 and 100% sustainable materials by 2050, the application of locally produced reclaimed rubber presents a promising opportunity not only to improve production efficiency but also to support environmental sustainability.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The used tire ecosystem in the Jabodetabek and West Java regions holds significant potential for collection and processing, with an estimated monthly volume of used tires of 2,860 units. The supply chain

encompasses multiple actors, including manufacturers, distributors, tire retailers, processing industries, and various specialised facilities, such as retread tire factories, pyrolysis plants, and cement producers. Used tires that are still in usable condition are retreaded for reuse. At the same time, those no longer suitable for use are repurposed for various industrial applications, such as lime kilns, used tire suppliers, pyrolysis plants, tire artisans, and tire decorators. However, several key challenges hinder the optimal utilisation of used tires. These include limited storage facilities, low awareness of the economic value of tire waste, and conventional management practices. To enhance the efficiency of the raw material supply chain and support the growth of the reclaimed rubber industry, there is a pressing need for stronger collaboration among stakeholders and the adoption of advanced recycling technologies. Such efforts are crucial in helping PT Bridgestone achieve its sustainability targets: a 40% increase in recycled materials by 2030 and 100% sustainable materials by 2050.

Recomendations

Although reclaimed rubber has significant potential to support the circular economy and promote environmental sustainability, the current laboratory-scale production costs remain uncompetitive compared to those of imported products. Therefore, it is essential to develop more efficient and advanced processing technologies to strengthen the used tire supply chain and support the growth of the reclaimed rubber industry.

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