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The Sustainable Communities and Waste Hub acknowledges all Aboriginal and Torres Strait Islander Traditional Custodians of Country and recognises their continuing connection to land, sea, culture, and community. We pay our respects to Elders past, present, and emerging. We support Aboriginal and Torres Strait Islander peoples and their aspirations to maintain, protect and manage their culture, language, land and sea Country and heritage.

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Executive Summary

This report delves into different dimensions of synthetic turf, tracing its historical evolution, evaluating its current application and critically assessing its environmental, health and lifestyle impacts. Originating in the 1960s as a solution to maintaining natural grass in indoor sports facilities, synthetic turf has evolved significantly, progressing through three distinct generations. Each iteration introduced technological improvements aimed at enhancing durability, playability, and safety, while increasingly emulating the look and feel of natural grass.

The report provides an in-depth comparison between synthetic turf and natural grass, analyzing parameters such as installation and maintenance costs, hydrological characteristics, durability, aesthetic appeal and environmental adaptability. While synthetic turf offers advantages like high durability, consistent performance across diverse climates, and reduced maintenance requirements, it also presents challenges. These include higher initial installation costs, elevated surface temperatures, limited recyclability, and potential health and environmental risks from its components.

A critical focus of the report is the environmental footprint of synthetic turf systems, with key concerns including the leaching of heavy metals and polyaromatic hydrocarbons (PAHs)., microplastics pollution from infill materials and fibres, and the release of volatile organic compounds (VOCs).. The urban heat island effect caused by synthetic turf's heat retention is highlighted as a pressing issue, along with its lack of ecosystem services such as carbon sequestration, biodiversity support and natural water filtration provided by natural grass.

The lifecycle analysis (LCA) offers a nuanced perspective on the trade-offs between synthetic and natural turf. Synthetic turf systems, while reducing water usage and chemical inputs during maintenance, exhibit higher greenhouse gas (GHG) emissions and energy demands during manufacturing. The report emphasizes the need for sustainable innovations, including the development of biodegradable infill materials, design for disassembly, and enhanced recyclability to mitigate end-of-life disposal challenges. Recycling efforts, while promising, face hurdles due to the complex multi-layered composition of synthetic turf, which complicates material separation and recovery.

Regulatory frameworks across key regions, including the European Union, the United States. And Australia, are analyzed, revealing diverse approaches to addressing the risks associated with synthetic turf. The EU stands out with its stringent regulations on microplastics, heavy metals and PAHs, while the U.S. and Australia exhibit gaps in policy enforcements and research. Initiatives such as product stewardship schemes and extended producer responsibility (EPR) are recommended to encourage sustainable practices and circular economy integration.

Emerging opportunities in the synthetic turf industry focus on improving environmental performance. These include advancements in eco-friendly infill alternatives, modular turf designs for easier recycling, and innovations in manufacturing processes to reduce carbon footprints. Furthermore, the report underscores the importance of ongoing research to assess long-term environmental impacts, particularly concerning microplastics, PAHs, and other contaminants.

In conclusion, this report offers a holistic view of synthetic turf as both an engineering achievement and an environmental challenge. It highlights the need for a balanced approach that integrates technological innovation, regulatory oversight, and collaborative stakeholder efforts to maximize the benefits of synthetic turf while minimizing its ecological footprint. This

comprehensive analysis aims to inform decision-makers, industry leaders, and researchers. Providing actionable insights for advancing sustainable practices in the synthetic turf sector.

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1. Introduction

The advent of synthetic turf in the 1960s marked a significant paradigm shift in the landscape of sports surfaces and urban greenery. The innovative technology, initially developed as a solution to the challenges of maintaining natural grass in indoor stadiums, has since evolved into a complex and multifaceted industry with far-reaching implications for sports, urban planning, and environmental management [1, 2].

The journey of synthetic turf can be traced back to 1962, when Monsanto, developed Chem Grass, a short-fiber, dense nylon carpet to replace urban schoolyard concrete. Its first installation in a major sporting venue was at the Houston Astrodome in 1966, an event that gave birth to the now-iconic "AstroTurf" brand. This first-generation synthetic turf, characterized by short plastic fibers without infill, represented a rudimentary attempt to replicate the visual aesthetics of natural grass. However, its hard surface and lack of shock absorption properties soon became apparent limitations, prompting further technological advancements, such as use of a closed-cell, elastomeric foam pad between the compacted soil and carpet to closely mimic natural turf [3], implemented in Houston Astrodome.
The evolutionary trend of synthetic turf has been marked by distinct generational improvements. The second generation, introduced in the 1980s, incorporated sand infill between the fibers, a modification that significantly enhanced the turf's stability and playability. This innovation led to wider adoption in sports facilities, although concerns regarding player safety and performance persisted. [4]. The emergence of third-generation synthetic turf started in the late 1990s when a technological leap characterized by longer fibers and the introduction of rubber infill was used with sand. The design innovation substantially improved the shock absorption and playing characteristics, more closely approximating the biomechanical properties of natural grass. [4].

Synthetic turf is increasingly regarded as a viable substitute for natural grass playing surfaces, particularly in environments where the growing and maintenance of natural grass is impractical, or costs are prohibitively too high. However, both natural grass and Synthetic turf have distinct advantages and disadvantages, which are crucial to consider when selecting an appropriate surface. The table provides a detailed comparison of each option.

Table 1: Comparative Analysis of Natural Grass and Synthetic Turf: Performance Characteristics, Environmental Impacts, and Sustainability Considerations

Parameter	Natural Grass	Synthetic Turf	Ref
Installation and Maintenance Cost	Low initial installation cost. High annual maintenance expense due to water, fertilizer, and labour requirements	High upfront installation cost. Lower annual maintenance expenses. Cost-effectiveness increases with usage frequency.	[5]
Aesthetic Properties	Visually appealing with natural odor, requires consistent maintenance for optimal appearance	Maintains consistent appearance year-round. Potential for color fading and rubber odour emission under high temperatures	[5]
Durability and Usage Capacity	Limited wear resistance; requires recovery periods. Typical usage: 20 hours/week or 680 hours/year for three seasons	High wear resistance. Minimal recovery time needed. Can sustain up to 3000 hours of annual play	[6]

Parameter	Natural Grass	Synthetic Turf	Ref
Environmental Adaptability	Growth limitations in extreme climates (arid or cold); challenging in low-light conditions	Versatile installation in diverse environments, including indoor facilities	[7]
Hydrological Characteristics	Susceptible to waterlogging; natural water filtration and groundwater recharge	Excellent drainage due to porous structure and engineered systems; immediate usability post-precipitation	[8]
Water Conservation	High irrigation demands	Minimal irrigation requirements; occasional watering for surface cooling and cleaning	[8]
Maintenance Requirements	Regular mowing, fertilization, and pest control; utilize fossil fuels and chemicals	Periodic sanitation, raking, and vacuuming; eliminate need for chemical treatments.	[5]
Player Safety Considerations	Established safety profile; potential hazards from uneven surfaces or animal activity	Comparable safety to natural grass; consistent surface reduces certain injury risks	[4, 9]
Environmental Impact	Carbon sequestration capabilities; supports biodiversity; emits biogenic VOCs	Potential environmental concerns; raw material consumption, elevated surface temperatures (up to 20°C higher than natural grass), GHG emissions from production and transport	[10, 11]
Life Cycle Considerations	Indefinite Lifespan with proper maintenance	Typical lifespan of 8-10 years; end-of-life disposal challenges due to limited recyclability.	[12]

Environmental considerations have become increasingly paramount in Synthetic turf development, particularly its infill material. Tire crumb rubber, a common infill material, has been found to contain a range of organic contaminants and heavy metals that can potentially volatile into the air and leach into percolating rainwater. [13, 14]. Research has examined the potential release of contaminants from turf components, such as zinc from recycled tire rubber, and the effectiveness of various testing methods for assessing environmental risks. [14]. A comparative assessment of chemical contents in various infill materials revealed that while no infill material was entirely free of concerns, several alternatives are likely to be somewhat safer than tire crumb. [13].

Environmental and health risk assessments have shown mixed results. Some studies indicate that the concentrations of volatile and semi-volatile organic compounds in the air Synthetic turf fields were typically not higher than the local background levels and the concentrations of heavy metals and organic contaminants in field drainages were generally below regulatory limits. [15]. However, recent research has identified the presence of environmentally persistent free radicals (EPFRs) in crumb rubber particles in the ambient air surrounding Synthetic turf fields with concentrations increasing with the operating years of the fields. [16]. This finding introduces a new pathway of human exposure to crumb rubber with EPFRs, potentially increasing health risks.
Life cycle assessments suggest that the environmental impacts of Synthetic turf fields may be lower than equivalent grass fields in some aspects. [15]. However, the potential release

of microplastics from Synthetic turf remains a concern, although recent studies indicate that their impact might be less significant than initially thought when compared to traditional environmental impacts [17]. This conclusion, however, may be limited by current assessment methods, that often underrepresent the complex long-term ecological, chemical, and indirect effects of microplastics, potentially underestimating their broader environmental risk. To address these environmental challenges, there is a growing focus on developing eco-friendly alternatives, such as using wood-based materials as infill and implementing more sustainable production and disposal practices for Synthetic turf systems [13, 18]. As the Synthetic turf industry continues to evolve, several challenges and opportunities emerge:

- The development of eco-friendly alternatives to traditional infill materials.
- Improving the comprehensive environmental impact evaluation of Synthetic turf systems throughout their lifecycle.
- Continuing the ongoing research to quantify and mitigate the microplastic emission from the Synthetic turf system.
- Improve the recyclability of synthetic turf components to develop closed-loop systems for material recovery.
- Addressing concerns about potential leaching of contaminants from infill materials like heavy metals and organic compounds.

This report aims to provide a comprehensive analysis of synthetic turf as a material engineering challenge, focusing on sustainability and environmental impact. It will examine the various components and materials used in synthetic turf systems, explore different types of synthetic turf, and assess their environmental impacts in detail. By synthesizing current research on material innovations, life cycle assessments, and environmental contaminations, this study seeks to contribute to the ongoing dialogue on developing sustainable and high-performance sports surfaces with minimal ecological footprint.

1.1. Global Status and Market Trend

The synthetic turf market has experienced significant growth globally, driven by various factors including environmental considerations and water conservation. Manufacturers have positioned synthetic turf as an environmentally friendly alternative to natural grass particularly due to its use of recycled materials and water-saving potential [15, 19].

One of the key environmental claims made by manufacturers is the use of recycled tire rubber in synthetic turf production. This approach addresses the significant challenge of managing the huge amount of scrap rubber tires generated annually. As per U.S. Tire Manufacturers Association's 2021 Scrap Tire Management Summary, around 32% (or 1.4 million tons) of tire crumb was generated from the total collected waste tires, which 22% was used in sports surface applications, which amounts to 0.3 million tons in 2021 alone [20].

The global synthetic turf market has been experiencing substantial growth, with market values exceeding USD 2.7 billion in 2019 with a projected CAGR of 5.2% from 2019 to 2025 [21]. China's synthetic turf production and market size are also experiencing rapid acceleration. This growth is partly attributed to the promotion of synthetic turf as a cost-effective and user-friendly alternative to natural grass, suitable for both residential lawns and sports fields.

Water conservation is another significant driver of synthetic turf adoption, particularly in arid regions. In the United States, a full-size synthetic turf sports field can save 1.9-3.8 million liters of water annually. This water-saving potential has led many water conservation institutions and city councils in dry regions of the US to offer financial incentives for replacing natural grass in residential lawns with synthetic turf [22].

1.2. Scenario of Synthetic Turf in Australia

Synthetic turf has been a part of Australia's sporting and urban environment for several decades. The history of synthetic grass in Australia dates back to the 1970s when it was first introduced for sports fields, particularly in cricket and tennis. However, its widespread adoption began in the early 2000s, driven by water scarcity concerns and the need for low-maintenance alternatives to natural grass.
In recent years, the synthetic turf market in Australia has experienced significant growth. The market size is valued at AUD 167.1 million in 2024; with a CAGR of 3.2% increase for businesses and a 2.7% decrease in market size between 2019 and 2024 [23]. This growth has been attributed to factors like:

- Increasing urbanization and the need for durable, low-maintenance landscaping solutions.
- Rising popularity of synthetic turf in sports facilities, particularly for cricket and football fields.
- Growing awareness of water conservation and sustainability practices.
- Technological advancements in synthetic turf manufacturing, leading to improved quality and performance.

The adoption of synthetic turf in Australia has been particularly notable in sports sector. Many professional sports venues, such as the Melbourne Cricket Ground and Adelaide Oval, have incorporated synthetic turf in their facilities. There has also been installation of third generation synthetic turf in soccer fields across Australia, and other outdoor sports precinct which are commonly used for Australian rules football and cricket (outfields) [24]. Additionally, local councils and schools are increasingly opting for synthetic turf in public spaces and playgrounds due to its durability and cost-effectiveness in the long run.

2. Components and Types of Synthetic Turf

Synthetic turf systems have undergone significant evolution since their inception, driven by advancement in polymer science and materials engineering, thus contemporary synthetic turf systems exhibit a complex, multi-layered structure, typically comprising primary components of grass/pile, infill material and backing system, with other layers like shock pad, performance and stabilizing infill, and extra backing layer added as per the application area.

1. **Synthetic grass fibers:** These are predominantly manufactured from polyethylene, polypropylene, or nylon, engineered to emulate the morphological and functional attributes of natural glass blades. Recent advancements in polymer science have facilitated the development of multi-shaped fibers, enhancing durability and performance metrics.

2. **Backing system:** The structural foundation of the turf system typically consists of a composite mixture of polyolefins, polyamide 6, polypropylene, and/or polyurethane. This backing provides essential structural integrity (primary backing) and facilitates drainage (secondary backing).

3. **Infill material:** This layer serves multiple functions such as stabilization, shock absorption, and modulation of ball bounce characteristics. The infill composition varies widely, encompassing materials such as crumb rubber (often derived from recycled tires), silica sand, organic substances (such as cork and coconut husks), and thermoplastic elastomers (TPE). The selection and proportion of these materials significantly influence the turf's performance and environmental impact.

Table 2: Composition of materials used in Synthetic Turf [24]

	First Generation	**Second Generation**	**Third Generation**
Characteristics	Hard and abrasive with fibers susceptible to UV degradation	Durable fibers with better stability	Soft fibers and properties close to natural turfs
Turf Fiber	Short pile (10-12mm) made of Polyamide (Nylon) fibers	Medium pile (20-35mm) made of monofilament or fibrillated polypropylene fibers	Long pile (40-65 mm) made of monofilament or fibrillated polyethylene or polypropylene fibers
Infill	Unfilled	With rounded sand	**Synthetic materials:** styrene-butadiene-rubber, thermoplastic elastomer (TPE), Ethylene Propylene Diene Monomer (EPD) **Natural materials:** Sand, cork, soft oak,
Backing	Foam backing	Carper backing with drainage	Primary backing: polypropylene and polyester Secondary backing: Polyurethane and latex for anchoring
Shock Pad	None	Only present in latter stage of development	Normally included and made of foam, SBR, textile, PE, PU or PP
Base	None	None	Compacted materials: asphalt, geotextile, drainage system and levelling layer

The composition and design of synthetic turf significantly influence its performance characteristics and environmental impact. Recent research has focused on optimizing these components to enhance player safety, improve playing conditions, and replicate natural grass behavior. Studies have investigated the influence of fiber density, fiber length, infill composition, and surface compaction on rotational traction and athlete biomechanics [25], and have been consistently evolved the design and material composition of synthetic turf to make it similar to natural turf.

2.1. Turf Fiber Materials

Synthetic turf grass fibers are generally made from two groups of polymers: polyolefin (polyethylene and polypropylene) and less common polyamide (nylon). These polymers are usually blended to enhance the properties of the grass fibers.

Polyethylene is the predominant material used in synthetic turf fibers due to its close resemblance with natural grass and requisite for minimal maintenance with occasional brushing and raking but is more susceptible to UV degradation and abrasion. Likewise, polypropylene has higher resistance to moisture but has inferior mechanical properties. Polyamide based fiber material made of nylon are also commonly used in high end applications and sports field due to its superior mechanical properties, and its ability to maintain its shape ion high temperature makes it ideal for hot environment.

Table 3: Comparison of Different Types of Synthetic Grass Fibres

Property	**Polyethylene**	**Polypropylene**	**Nylon**	**Ref**
Chemical Formula	$(C_2H_4)_n$	$(C_3H_6)_n$	Nylon 6: $(C_6H_{11}NO)_n$ Nylon 6,6: $(C_{12}H_{22}N_2O_2)_n)$	[26, 27]
Molecular Structure	Linear (HDPE/LLDPE)	Isotactic (high crystallinity)	Polyamide with high intermolecular bonding	[26, 27]
Tensile Strength	20-40 MPa	Lower than PE and nylon	70-80 MPa	[28]
Elongation at Break	100-600%	Limited elasticity	Very stiff	[27, 28]
UV Resistance	High with UV stabilizers	Moderate (less stable in high UV exposure)	High	[28]
Melting Point	115-135°C	160-165°C	>220°C	[26, 27]
Moisture Absorption	Very Low	Very Low	High (4-4.5%)	[28]
Texture	Soft, resembles natural grass	More delicate, less durable	Stiff, more durable	[26, 27]
Durability	High when blended with nylon	Prone to heat deformation	Highest durability and abrasion resistance	[27]
Cost	Moderate	Least expensive	Most expensive	[27]
Temperature Resistance	Less stable in high temperature	Deforms in high temperature	Maintains shape in high temperature	[26, 27]
Applications	Home lawns, play area	Landscaping in low-traffic area	Sports field and high-end applications	[4]

3. Behaviour of materials in synthetic turf

Among all the layers, infill of synthetic turf contains most material, with concentration of volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs) and heavy metals, which have been under extensive investigation for their dissipation mechanism and its impact on environment and human health. The tire rubber crumb used in infill can degrade due to oxidation, effect of ozone, heat and sunlight (UV), effecting its physical and chemical properties, thereby releasing the content of rubber into environment [15]. Similarly, recycled (used) tires are used for tire crumb in infill, which lacks anti-degradants and waxes which inhibit degradation of tires during their lifetime, which further aids in degradation of the infill layer. Also, the higher surface area of the tire crumb provided larger exposed area to the environmental stressor, thus increasing volatilization of organic contaminants in air and leaching heavy metals and chemical contaminants into water run-off [29].

3.1. Heavy metals

Tire crumb contains several heavy metals like zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), lead (Pb), iron (Fe) and cadmium (Cd) [30], which are non-degradable and have chances of contaminating water-runoff from the turf. Studies have shown that zinc is the most common metal, comprising two-third metal concentration in synthetic turf, followed by iron, magnesium, aluminum and potassium [31]. Zinc is found in oxide form (ZnO), which is used as vulcanization activator, and iron comes from steel wires used in tires, with remaining metals used as silicates and adhesion promoter [31]. Upon further investigation, it was found crumb rubbers contains the most amount of heavy metals compared to other layers like blades, backing and geotextiles [32].

There are presence of encapsulated lead chromate pigment in earlier generation of turf blades, with higher level of lead found in turf fiber made of nylon or PE/nylon blend, with comparatively very less lead content in polyethylene only fibers [33]. In addition, there are other metals like Al (1.2-2.1 mg/g), Fe(2.7-4.0 mg/g), and Cr, Cu, Mg, Ni, Sn and Ti (within range of 0.01-1 mg/g) found in the turf fibers [34], which are introduced in coloring pigments and UV stabilizers for the aesthetic and performance enhancement. The later generation of turf blades and carpet backing have quite low presence of encapsulated lead chromate pigment (<0.001 mg/g), since same materials are used to make other polymer based consumer product [33].

DIN 18035-7, a German standard commonly used in Europe, outlines requirement for installation and maintenance of synthetic turf, provides environmental and safety guidelines, particularly release of harmful chemicals like heavy metals from synthetic turf into environment. Table 4 shows the limit for the release of heavy metals in the environment from synthetic turf, with all limits set through nitrification toxicity test [35].

Table 4: DIN 180.5-7 Standard Limit for Heavy Metals in Synthetic Turf [35]

Metal	Requirement
Lead (Pb)	≤ 0.04 mg/l
Cadmium (Cd)	≤ 0.005 mg/l
Chromium total	≤ 0.05 mg/l
Chromium VI (CrVI)	≤ 0.008 mg/l
Mercury (Hg)	≤ 0.001 mg/l
Zinc (Zn)	≤ 3.0 mg/l or ≤0.5 mg/l
Tin (Sn)	≤ 0.05 mg/l

3.2. Volatile organic compounds (VOCs)

VOCs in synthetic turfs primarily originate from the infill, specifically in the rubber crumb. These compounds are mainly derived from solvents used in the rubber conversion industry, binding agents for different rubber layers, mold-releasing agents, and tire production processes like extruding, curing press spray, and finishing paint [32]. While no specific regulations exist for VOCs in crumb rubber its water solubility and high volatility have led to regulators setting exposure limits in air, drinking water, and water ways.

Research on VOCs in crumb rubber has shown that while increased emission factors for certain semi-volatile organic compounds (SVOCs) and VOCs such as methyl isobutyl ketone and benzothiazole occur at elevated temperature (60°C) [36, 37], the observed concentrations generally remain within safe limits and do not pose significant hazards [32]. Notably, toluene has been consistently detected in the air synthetic pitches, but it's level remains below regulated thresholds. Additionally, studies indicate that indoor synthetic turf fields tend to exhibit higher VOC concentrations compared to outdoor settings [32]. Given that synthetic turf can reach elevated temperatures in warmer climates, further investigation into the air quality above these fields is required focused on monitoring VOC emissions.

3.3. Polyaromatic hydrocarbons (PAHs)

The rubber infill in synthetic turf contains PAHs which come from highly aromatic oils added as extender oil and carbon black, which are used as reinforcement filler during production. US EPA has identified 16 different PAHs commonly found and of major concern from crumb rubber from tires. [32]. Due to this, European regulations have been restricting the use of aromatic oils since the 2000s, to reduce PAH generation from tires. [15], while carbon black use has been still unregulated, leading to PAHs generation from granulated tires used in synthetic turf.

Table 5: PAHs of concern from tires for US EPA and EU [30, 32]

PAH of Concern		**Listed by**
NAP	Naphthalene	US EPA
ACY	Acenaphthylene	US EPA
ACE	Acenaphthalene	US EPA
FLU	Fluorene	US EPA
PHN	Phenanthrene	US EPA
ANC	Antharacene	US EPA
FLA	Fluoranthene	US EPA
PYR	Pyrene	US EPA
BaA	Benzo[a]anthracene	US EPA and EU
CHY	Chrysene	US EPA and EU
BbF	Benzo[b]fluoranthene	US EPA and EU
BkF	Benzo[k]fluoranthene	US EPA and EU
BaP	Benzo[a]pyrene	US EPA and EU
IND	Indeno[1,2,3-cd]perylene	US EPA
DBahA	Dibenzo[a,h]anthracene	US EPA and EU
BghiP	Benzo[g,h,i]perylene	US EPA
BeP	Benzo[e]pyrene	EU
BjF	Benxo[j]fluranthene	EU

Recent studies have revealed important insights into the presence and concentrations of PAHs in crumb rubber infill used in synthetic turf. PAHs primarily originate from high-temperature processes during tire production, rather than from the recycling process itself, indicating that the manufacturing origin of tires is a key factor in determining PAH concentrations, rather than from the granular size or recycling methods. [32]. Notably, pile blades have been found to contain very minimal PAH content compared to rubber-infill [32]Often exhibit higher PAH levels in the surroundings compared to outdoor environments [32]. These findings highlight the complexity of PAH presence in crumb rubber infill and underscore the various factors influencing their concentrations and potential exposure risks.

3.4. Microplastics

Microplastics are solid particles of non-biodegradable plastic or rubber measuring 5 mm or less and have been a growing concern for synthetic turf systems. These particles can form unintentionally through wear and tear or be deliberately manufactured for specific purposes. Bertling et al, from their studies of synthetic turf systems in Germany and Switzerland, estimated that around 3 tonnes of performance infill gets eroded every year, with lower-density infill having a higher chance of loss. [38].

To address this issue European Standards Committee (CEN) has provided guidance for minimizing infill dispersion through improved design, operation, and maintenance procedures. [39]. These measures include physical barriers, boot cleaning stations, and drainage systems with slit traps. However, microplastic formation is not limited to infill materials. The synthetic turf filaments themselves break down over time due to UV radiation, contributing to microplastic pollution [40]. Bertling et al, observed fiber loss of 50 kg to 1 tonne per year in the same fields, though the exact mechanism of loss needs further investigation [38].

4. Impact of Synthetic Turf in Environment

4.1. Air Quality Impacts

Synthetic turf can significantly affect local air quality through two primary mechanisms:

- **Chemical Emissions**: Synthetic turf can dissipate certain gases including VOCs and SVOCs, concentrated in the infill layer onto the air at a higher temperature [32], with the main route of human exposure through inhalation. Likewise, off-gassing chemicals like PAHs and phthalates can be produced from new installations, which typically decreases over time [32].

- **Temperature and Heat Island Effect:** Synthetic turf tends to absorb and retain more heat than natural turf, contributing to the urban heat island effect [10], with studies showing at least 10- 15°C higher temperature for synthetic turf compared to natural turf [41-43]. The increased surface temperature can lead to higher ambient air temperatures in the surrounding area, potentially affecting local air quality by promoting the formation of ground-level ozone (tropospheric ozone) [44], a key component of photochemical smog in urban environments.

- **Absence of biogenic air purification system:** Unlike natural turf grass, synthetic turf lacks the capacity for biogenic air purification [45]. Natural grass engages in photosynthesis, consuming carbon dioxide and producing oxygen. Additionally, the leaf surface area of natural grass acts as a biofilter, trapping airborne particulates and absorbing gaseous pollutants [46]. The absence of this ecosystem may result in comparatively lower levels of air quality.

- **Particulate material generation:** Synthetic turf systems contribute to particulate matter (PM) in the atmosphere through two primary mechanisms: crumb rubber attrition and microplastic shedding. The mechanical breakdown of crumb rubber infill generates fine particulates. Studies have revealed that these particles can range from nanoscale to microscale dimensions, posing potential respiratory concerns [47]. Likewise, the polymer in turf blades can also release microplastic into the environment, from PM2.5 to PM10 levels making it airborne [40].

- **Maintenance-related emissions:** The maintenance process for synthetic turf can introduce additional air quality concerns through the use of chemical-based cleansing agents like antimicrobial treatments and cleaning agents [48]. Similarly, the use of power equipment for turf maintenance like leaf blowers, and mechanical; brushes can re-suspend settled particulates increasing the concentration of PM levels in the surroundings [48].

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4.2. Water Resource Impacts

Synthetic turf can have positive impacts like less consumption of water for maintenance compared to natural turf, while also can aid in increased runoff due to its non-porous nature with an increased amount of particulate and chemical footprint in the runoff.

- **Water Conservation:** One of the primary benefits of synthetic turf in terms of water resources is water conservation, as it does not require regular watering, unlike natural grass. This can lead to significant water savings, especially in and/or drought-prone regions [8], with studies showing around 33 to 50% of savings (355-710 liter per sq. meter), on a per annum basis [49]. But studies have also shown that the heat island phenomenon around synthetic turf is due to its heat retention properties [41-43], a considerable amount of water is required to cool it down to make it usable for longer periods of time [49].

- **Stormwater Runoff and Water Quality:** The modern synthetic turf systems are equipped with complex drainage systems with and without pipes, and aggregate base composed of granulated sand. These turf systems help in stormwater management by delaying and storing rainfall, potentially reducing stress on stormwater networks. However, the hydrologic implications of synthetic turfs on runoff and infiltration are not well-documented [50].

  Pollution through field infiltration is generally mitigated using sand infill and calcite-rich base aggregate in third-generation systems, as sand is known to be an effective filter for many pollutants while calcite can reduce zinc levels through absorption. It has been seen that 11.6% calcite composition in infill can reduce zinc concentration from 1000µg/L to 50 µg/L [34]. Moreover, calcite has also shown tendency to absorb PAHs from water runoff [51]. Virgin rubber infill appears to release less zinc and total toxicants compared to used tire rubber crumb, with zinc (associated with the rubber vulcanization process) often identified as the most significant toxicant risk to aquatic ecosystems, with concentrations often exceeding freshwater ecosystems guidelines [52].

- **Groundwater Recharge and Contamination:** The impervious nature of many synthetic turf systems can reduce infiltration rates compared to natural soil, potentially decreasing groundwater recharge. A study by Cheng et al. found that synthetic turf reduced infiltration by 70% compared to natural grass [15]. However, the impact varies on the specific design and underlying drainage system of the synthetic turf installation. Metals like Zinc, which originated from rubber infill, has been reported to reach 1000 μ/liter significantly above regulatory standards [11]. Other potential contaminants include PAHs and various organic compounds. Additionally, the breakdown of the synthetic turf fibers can also release microplastics, which may infiltrate groundwater systems. There are estimations showing that 40-100 kg of microplastic can percolate to groundwater from synthetic turf each year [53].

4.3. Soil and Ecosystem Impacts

- **Soil Compaction:** The installation of synthetic turf often involves soil compaction to form a stable base. This compaction reduces soil porosity limiting the movement of air, water and nutrients, which can negatively impact soil health and reduce its ability to support plant life.

- **Biodiversity Loss:** Natural grass supports a diverse ecosystem of microorganisms, insects and other organisms that contribute to soil health. Synthetic turf, however, creates a barrier that disrupts this ecosystem, leading to a decline in soil diversity. Likewise, the leaching of several organic chemical, heavy metals and plasticizers can leach into soil over time, contaminating the soil gradually and harming plants and organisms.

- **Nutrition Depletion:** The presence of an impervious synthetic layer and absence of natural grass, which contributes to organic matter to the soil can lead to nutrient depletion over time. Likewise, the unnatural water runoff and infiltration mechanism due to synthetic fiber leads to soil erosion and nutrient depletion.

4.4. Microplastic Pollution

Microplastic from synthetic turf can be transported to surrounding soil and water systems through surface runoff, drainage systems and direct dispersion. Once dispersed, microplastics can accumulate in terrestrial and aquatic ecosystems. They can be ingested by soil organisms and aquatic life, leading to potential bioaccumulation and biomagnification in food chain. These microplastic often act as carriers for PAHs and heavy metals, leading to embedment of these elements in bio-system, which can lead to physical blockages, reduced feeding and exposure to toxic chemicals. The long-term ecological impacts include potential disruptions to food webs and ecosystem functions.

4.5. Carbon Footprint and Life Cycle Considerations

- **Manufacturing Phase:** The production of synthetic turf involves the manufacturing of plastic materials and deriving crumb rubber infill often from used tires, which is energy intensive and generates substantial greenhouse gas (GHG) emissions [14].The primary materials used such as polyethylene and polypropylene are derived from fossil fuels, contributing to the carbon footprint. Similar, pattern has been observed through comparative LCA analysis between synthetic and natural turf, where higher energy consumption is forecasted with significantly more GHGs production for synthetic turf [54].

- **End-of-life Disposal:** The disposal of synthetic turf poses significant environmental challenges. The materials used in synthetic turf are not biodegradable, leading to a long-term environmental persistence, and with average lifespan of 8-10 years, synthetic turf contributes significantly to landfill waste [14]. There has been few approaches to divert the EOL synthetic turf for recycling, but the complex multilayered components of the synthetic turf system is posing as a major challenge to overcome for efficient resource recovery [55].

5. Impacts of Synthetic Turf in Human

Synthetic turf fields have raised concerns due to the presence of toxic and carcinogenic chemicals. These pollutants can potentially be released into the environment, posing health risks to users through various exposure pathways such as inhalation, dermal uptake, and ingestion. This section discusses the potential health impacts, supported by various studies and assessments.

- **Inhalation:** Inhalation of VOCs, SVOCs, and particulate matter from tire rubber crumbs is a primary exposure pathway. Field assessments have revealed low concentrations of VOCs and PAHs in the air above synthetic turf fields, generally not at levels of concern for human health [56-58]. Adequate ventilation in indoor areas with synthetic turf can mitigate health risks. Both indoor and outdoor synthetic turf have not shown increased risks from exposure to respirable particulate matter (PM2.5 and PM10) [59-61]. One study indicated a potential cancer risk for professional athletes with intensive long-term exposure (5h/day, 5 days/week for 30 years), but no elevated risk for amateur or occasional users [62]. Significant health risks may occur for workers installing synthetic turf in poorly ventilated conditions over extended periods (>5 years) [59].

- **Ingestion:** Incidental or intentional ingestion primarily affects children through hand-in-mouth activity. The degree of exposure depends on factors such as frequency of hand-to-playground contact, field use, and chemical transfer efficiencies [15]. Multiple studies have investigated the effects of direct ingestion, with findings suggesting no significant health effects, even at varying exposure levels [63, 64]. For both adults and children, synthetic turf fields and playgrounds are generally considered to pose a low risk to human health through oral exposure. While specific ingestion rates are not provided, studies indicate that the amount ingested through typical use scenarios is unlikely to cause adverse health effects [65].

- **Dermal Uptake:** Toxic chemicals leached from rubber crumbs can enter the body through skin contact. Several studies have concluded that the number of toxic substances absorbed through skin contact is too small to create negative health effects, including allergies, for both adults and children [66, 67]. Biological studies monitoring biological markers (1-hydroxypyrene) showed insignificant amounts of PAH in the urine of football players after rigorous skin contact with rubber crumbs, indicating negligible uptake of PAH through the dermal pathway [68, 69]. The short contact time with rubber crumbs and the natural protection of the human body reduces the likelihood of significant dermal absorption causing health problems.

Thus, although all three pathways present potential risks, current research generally indicates low health risks for typical users of synthetic turf fields. However, ongoing studies continue to investigate potential long-term effects and emerging concerns, particularly for scenarios involving prolonged and intensive exposure.

5.1. Aspects of Health Impact in Human

In an extensive report from the Chief Scientist and Engineer from the NSW Government, the impact of synthetic turf on human health has been divided into five broad categories, incorporating direct and indirect exposure [70], as shown in Table 6.

Table 6: Classification of Health Impact on Human from Synthetic Turf

Classification	Description	Impact Method
Physical Injury	Synthetic material can retain heat levels that can cause burn; the hardness and abrasiveness nature of turf can cause bodily injury.	Direct
Heat-related impact	The heat retention behavior of synthetic turf causes thermal discomfort around its proximity.	Direct and Indirect
Chemical, microplastic, and microbiological health risk	Microplastic generated from synthetic turf poses significant health risks and can also be a potential breeding ground for pathogens.	Direct
Chemical leachate runoff	Leaching of chemicals and additives to soil and nearby water sources can introduce toxic elements.	Indirect
Mental and social dimensions of health	The substitution of natural turf with synthetic turf reduces the exposure of the community to natural spaces. Impacting community cohesion and mental health.	Indirect

Physical injuries from synthetic turf were common in first-generation turfs due to their hard and more abrasive surface, leading to frequent knee injury and skin abrasion [71]. These impacts have been vastly mitigated in newer-generation turf, where the blades and surface are designed to mimic natural turf, providing users with comfortable playable surfaces. However, the issue of heat retention remained due to the use of synthetic materials. At elevated temperatures, the turf surface tends to retain heat increasing the temperature of the surface to potentially leading to burns [72]. Similarly, biomechanical studies have shown that synthetic turf exerts greater rotation torque in the player shoe-surface interface, compared to natural turf [73], which alongside with hardness of the field can amplify the physical impact on the player. Likewise, during hot weather, synthetic turf can get up to 70°C [74], with studies showing cutaneous thermal injury occurring above 44°C [75].

The crumb rubber and pile blades have low albedo and low specific heat capacity, thus in the same ambient condition, synthetic turf heats significantly higher than natural turf [76, 77], and with time and continuous usage, the thermal condition of the synthetic turf deteriorates [77]. The air above synthetic turf (<15 cm) seems to have a higher air temperature (42.7°C) than natural turf (38.1°C) [76], posing a higher risk to children due to their physical stature and lower heat tolerance [78]. Similarly, the substitution of natural turf for synthetic turf also aids in the urban heat island (UHI) effect which results in 5-10°C higher air temperature at night time [79], which directly impacts young children, elderly people, and those with underlying respiratory and cardiovascular conditions [79].

The use of polymers like PP and PE in blades and crumb rubber in infill layer with polyester backing is current generation turfs containing several toxic and carcinogenic compounds like SVOCs, PAHs, VOCs, and heavy metals [15, 64]. These chemicals pose health risks through ingestion, dermal intake, and inhalation. The degradation of the synthetic material under the influence of heat, sun, and ozone exposure can also generate microplastic granules with at least half polymer content X, which is common in stormwater runoff having a harmful impact on soil and marine life [15, 64]. The leachate from synthetic turf systems mostly contains metals like zinc and PAHs and has tendency to leach out in high levels under laboratory conditions from crumb rubber X. The metal can come in contact through a dermal path through catchment runoff or also be inhaled through PAH volatilization, or through drinking water [31, 32].

There is limited behavioral and psychological research on the substitution of natural turf for synthetic turf in an urban environment to provide the community with open spaces for recreational and communal activities. Though WHO states that the urban green space with natural flora, grasslands, trees, and wetlands helps in a range of positive health impacts the comparative study with synthetic turf is very limited [80].

6. End-of-life (EOL) Management and Sustainability of Synthetic Turf

6.1. EOL Management

Synthetic turf generally has four options for end-of-life management: reuse, landfill, incineration, and recycling. Landfill and incineration have been the most common practices due to the heterogeneous complex layering of materials and their degradation in mechanical properties due to continuous usage and exposure to natural elements [81]. Recycling of synthetic turf is carried out by separating each layer and material but has very low efficiency due to the same issue of complex constituents and layering of materials [15].There has been commercial approach for granulation of used turf by shredding and palletization, to be used in new turf r other materials but the products have poor mechanical properties and thus only used for lower grade application (downcycling) [81].

Table 7: Different Materials Used in Current Generation of Synthetic Turf and their End-of-life management pathways X

	Materials	**Manufacturing Process**	**EOL Management**
Pile	PE, PP, Nylon and Pigments	Virgin polymer mixed with UV stabilizers and additives are heat-extruded into grass blades shapes	Landfill; downcycled into smaller pieces
Primary Backing	PP, PU	Non-woven textile to support fiber layer	Landfill
Secondary Backing	PU, Latex	Coated layer on back of primary backing and perforated for water sippage	Landfill
Stabilizing Infill	Silica Sand	From gravel pits, and coated with acrylic or elastomeric coating	Can be reused
	Styrene butadiene rubber (SBR)	Granulated rubber shredded using mechanical or cryogenic method	Recycled or landfilled
	SBR with sand		Recycled or landfilled
	Materials	**Manufacturing Process**	**EOL Management**

Performance Infill	Ethylene propylene diene monomer (EPDM)	Synthesized from virgin materials in granule form; fire retardant additives can be added	Recyclable
	Thermoplastic elastomer (TPE)	Synthesized from virgin materials into various granulated shapes	Recyclable
	Organic infills (plant-based fibers)	Can be used directly with antimicrobial treatment	Biodegradable
Shock Pad	PP, PE, PU, SBR	Varied thickness, density and additives as per application area and can made from virgin or recycled materials	Can be reused upto 3 rimes for same applications
Adhesives	Isocyanate, epoxy. Urethane, latex	Solvent dissolution method from virgin materials	Often discarded during recycling or landfilled

Re-use of synthetic turf is often mistakenly called recycling. True reuse involves repurposing the turf of its components in a similar function, while recycling requires processing before reuse. Equipment like the 'turf-muncher' has made removal easier, but on-site infill removal presents challenges. Contamination with sand is a major issue for recycling and re-use. Despite manufacturers' claims, direct reuse of removed infill in new pitches is not widespread. A CalRecycle study found only 25-50% of SBR infill was reused, with the rest landfilled [82]. The lack of clear end markets and the likelihood of lower-value applications make the case for re-use unfavorable [81].
Synthetic turf recycling faces significant challenges due to material contamination and complex composition. Few recyclers can achieve high-purity material outputs, primarily because sand infill contamination is difficult to separate, and turf is composed of multiple plastics. As a result, most recycling practices follow an "open loop" approach, where materials are downcycled into lower grade applications such as road cones, rubber tiles, pallets and boxes [83]. The ultimate goal of "closed loop" recycling, which should allow forming into new turf material remains attainable due to technical constraints and the permanent bonding of different materials in turf construction [84].

Recent technological advancements, such as "hot-melt" backing show promises for improved material separation during recycling [85]. However, this technology is still unproven in practice and not yet widely used. Recycling plants in North America and Europe have faced numerous obstacles, including contamination issues, insufficient turf inputs, competition from other disposal operators, and lack of support from turf manufacturers [81]. These challenges have led to the closure of many recycling facilities. The high cost of transport and deposit, ranging from USD 10,000 to 60,000 per pitch has created significant pressure to reduce expenses [81], thereby increasing instances of illegal disposal. This situation raises concerns about the potential for increased illegal; dumping of waste turfs, a problem that is expected to worsen as the number of worn-out turfs increases in due course of time.

The disposal of synthetic turf is predominantly influenced by the prevailing waste management principles in each country. Globally, landfilling remains the primary method, especially outside Europe and in Eastern Europe [86]. Countries with significant football turf installations, such as Canada, USA, and Australia rely heavily on landfills minimal incineration, and low recycling rates [86]. In nations like Morocco and Turkey, where unregulated dumping are common, the low disposal costs may hinder recycling efforts for synthetic turf unless specific industry incentives are implemented [81, 86]. Conversely, Western European countries have shifted towards incineration as the primary method for managing unrecycled waste, driven by landfill taxes and bans [81, 86]. Several European nations have implemented both measures, resulting in the incineration of almost all non-recycled waste. The United Kingdom has imposed one of the world's highest landfill taxes, promoting alternatives like incineration [81, 86]. Modern waste-to-energy incinerators have gate fees included in energy revenue, which can be reduced through energy sales and sometimes supported by renewable energy incentives or implicit subsidies.

6.2. Life Cycle Assessment

In a review of LCA for synthetic turf fields from a circular economy perspective, Abbas et al. [87], compared eight LCA studies with seven comparing synthetic turf to natural turf scenarios, where they found that synthetic turf generally performed better in terms of water and resource consumption, leading to reduced eutrophication and pollutant emissions during maintenance. However, synthetic turf requires higher energy consumption and generates more GHG during production, although these impacts can be mitigated by using recycled materials (like recycled tires as infill) or by using have longer usage time compared to natural turf. However, the LCA studies have often overlook the impact of VOCs, heavy metals, and PAHs from recycled tires, microplastic generation from blades and infill, the impact of UHI, and the use of chemical softeners for maintenance of the turf blades.

Natural turf, on the other hand, has lower GHG and energy requirements for production and may act as a carbon sink. Most studies did not identify significant lifecycle cost differences between synthetic and natural turf, but synthetic turf offers higher usability time and intensity of use. The LCA application to synthetic turf is limited by available data, underlying assumptions, and the need for proper EOL management. To improve LCA frameworks for synthetic turf, the authors suggest independently verifying manufacturers' claims, reviewing multiple data sets under different conditions, and collecting data on fields with similar activities and proximity. While developments in the EU should be monitored, caution is advised when translating findings to the Australian context due to differences in climate, material inputs, tire standards, and EOL infrastructures.

There have also been studies to incorporate a circular economy framework for the synthetic turf life cycle into all stages of its supply chain to make it more sustainable. outlines the key strategies for implementing a circular economy approach in the lifecycle of synthetic turf [88]. Each stage emphasizes sustainable practices, from material sourcing and design to EOL management, aimed at minimizing environmental impact and enhancing resource efficiency by adopting these strategies, stakeholders can contribute to a more sustainable future for synthetic turfs. [88].

Table 8: Circular Economy Strategies for Synthetic Turf

Stages	Key Strategies
Material Sourcing	• Use of recycled materials • Promote industrial symbiosis • Ensure functional recycling • Minimize environmental impact in manufacturing

Stages	Key Strategies
Design	• Customize product for specific uses
	• Design for disassembly/recycling • Implement modular design • Reduce harmful and toxic materials
Manufacturing	• Use renewable energy • Use efficient processes • Utilize locally sourced materials
Distribution and Sales	• Establish a material feedback loop market for synthetic materials
Consumption and Use	• Involve community in maintenance • Implement eco-=labelling and product information • Promote socially responsible consumption
Collection and Disposal	• Implement Extended Product Responsibility (EPR) • Incentivize Recycling • Establish clear separation methods • Ensure accessible recycling logistics
Recycling and Recovery	• Utilize by-products • Implement downcycling • Recover materials like sand infill which can be reused • Convert high calorific value materials to energy
Remanufacturing	• Enable partial refurbishment • Provide upgrading maintenance and repair services
End-of-life	• Ensure sustainable EOL management

7. Current State of Regulations on Synthetic Turf

Synthetic turf has started gaining popularity across the world but the research on its potential human impact and environmental health risk has been limited with wide arrays of government policies and regulations implemented across the globe. European Union, particularly has been proactive in taking regulatory approaches to mitigate the impact of synthetic turf, where the standards are formed around direct field exposures, microplastic generation from rubber crumb infill, and concentration of heavy metals, VOCs, PAHs, and PFAS in the turf [89].

7.1. European Union

EU created a law, Registration, Evaluation, Authorization and Restrictions of Chemicals (REACH) that makes registration of any chemicals imported or manufactured within the EU and formed the European Chemical Agency (ECHA) to implement it [90]. REACH with its committees like Committee for Risk Assessment (RAC) and the Committee for Socio-Economic Analysis (SEAC) keeps check on the European commission regarding potential policy formation and implementation considering the chemical composition, probable environmental and human health impact, and its constituent socio-economic repercussions [91].

The EU policy has been stringent on PAH and microplastic limitation. EU has set a limit of 1 ppm for products containing rubber or plastic that can come in direct dermal contact or chances of ingestion in humans, focusing on the blade layer and excluding any layers beneath it [30, 32], as shown in

Table 3. However, extensive studies has shown that the rubber infill in synthetic turf exceeds the set limit for PAH. [64], showcasing the limitations of the EU policy. The total permissible PAH limit for all eight PAHs has been calculated to be 387 mg/kg, which was later reduced to 20 mg/kg in 2019, considering the presence of toxic elements in tire crumbs. [92]. However, there are no restrictions or policies regarding the limitation of heavy metals (zinc, lead, cadmium, and manganese) in the European Union.

Similarly, ECHA has also proposed a ban on the use of microplastic in EU market products including synthetic turf, with a transition period of 6 years [93]. There also has been a proposal to set the limit on microplastic release from the field to 7g/m^2 [93]. Likewise, the European Committee for Standardization, in 2020, provided a general recommendation on minimizing microplastic infill in synthetic turf through design parameters. [94]. These approaches can be seen as a positive outreach by the EU to mitigate the impact of synthetic turfs.

7.2. United Kingdon

UK Reach, established in 2020, only has limitations for PAHs on extender oil in tire manufacturing, and for products that come in direct contact with skin or oral cavity, which is translated from EU regulations [95]. There are no active microplastic regulations for synthetic turf, despite earlier concerns raised by the Environmental Agency in 2009. The UK banned microplastics in cosmetics and personal care products in 2018 [96], but has made little effort to address microplastic pollution from crumb rubber infill. Individual countries within the UK can establish their own environmental regulations if they meet UK REACH requirements. Scotland aims to uphold EU environmental standards through the UK's withdrawal from the EU.

The Health and Safety Executive (HSE) monitors worker health and safety in Great Britain but has not reported any checks or enforcement actions on chemicals in synthetic turf infill and fibers between 2007 and 2017. While the HSE has produced guides for handling synthetic turf surfaces and crumb rubber infill, these do not adequately address potential health risks from the exposure.

7.3. USA

The USA’s environmental regulations for synthetic turf and crumb rubber infill are minimal at the federal level. There are no clear concentration limits for PAHs in solid products like crumb rubber, and no direct regulations for heavy metals in crumb rubber infill. The regulation of PFAS chemicals is ongoing, but it’s unclear if this applies to synthetic turf. The Federal Research Action Plan on recycled tire crumbs used on playing fields and playgrounds, initiated in 2016, is the most significant federal action on this issue. [97]. The EPA has also been working on PFAS regulation, including phasing out PFOA and requiring approval for long-chain PFAS chemicals [98].

The Microbead-Free Waters Act of 2015 banned microplastics in cosmetics. [98], but there is no federal regulation of microplastics in crumb rubber infill. The lack of conclusive studies on the health effects of synthetic turf field use has hindered the development of comprehensive federal policies. Most existing policies only apply to newly installed fields, and there is an absence of mandatory testing for synthetic turf and crumb rubber products.

7.4. Australia

Australia has implemented several regulatory frameworks to address environmental and health concerns related to synthetic turf and waste management, particularly focusing on tire recycling and product stewardship. These regulations aim to promote circular economy principles and reduce the environmental impact of products throughout their lifecycle. The Australian Recycling and Waste Reduction Act 2020 provides a national framework for managing the environmental health and safety products across their lifecycle [99]. This Act introduced restrictions on the export of waste tires, including processes styrene-butadiene rubber (SBR), which came into effect at the end of 2021. The Act emphasizes product stewardship, which places responsibility on those who design, produce, sell, or use a product to minimize its environmental impact, including EOL management. It allows for voluntary, co-regulatory, and mandatory product stewardship arrangements. Extended Product responsibility (EPR) schemes, a form of product stewardship, place primary responsibility on product producers and importers.

A relevant initiative is the Tire Product Stewardship Scheme, a voluntary, Australian Competition and Consumer Commission (ACCC) authorized industry framework [100]. This scheme aims to reduce the impacts of EOL tires, which are often used in the production of crumb rubber for synthetic turf. Australia currently lacks import standards for tires, leading to uncertainty about the composition of materials in imported tires. This uncertainty has prompted some councils to import SBR crumb, which is known to contain PAHs and heavy metals. Tire Stewardship Australia (TSA) is currently focusing on chemical and physical testing of tires to understand their composition and identify contaminants of concern [100].

The stagewise effort being carried out by the state government and the responsible bodies in Australia are limited where independent reports and guidelines are being drafted in accordance with the impact of synthetic turf and its control. NSW Chief Scientist conducted an independent review in collaboration with stakeholders ranging from local councils, and universities [70], which has been well received by the state government. This comprehensive independent review highlights the concerns of toxic chemicals in rubber infills and has called for more research and regulations. Similarly, (DPHI) has released draft guidelines for the use of synthetic turf in playing fields, as a follow-up to the NSW Chief Scientist independent report. This report aims to assist planners with information and case studies regarding the installation of synthetic turf and its probable impact on the environment and human health. [101].

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