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Developing a Sustainable Tennis Ball: A Comprehensive Analysis of Biodegradable Materials and LCA

Calvin Gonzalez

Regis High School, USA

ABSTRACT

The tennis ball industry significantly contributes to environmental waste due to the use of non-biodegradable materials. This escalating issue presents the need for sustainable alternatives in tennis ball manufacturing. This literature review investigates environmentally friendly materials that could replace current tennis ball components. By examining natural rubber alternatives derived from plants such as Hevea brasiliensis, Russian dandelion, and guayule, and evaluating biodegradable polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), the study assesses their viability as core materials. Additionally, organic textiles like hemp and flax fibers are considered for the felt covering due to their high tensile strength and reduced carbon footprints. In the end, the proposed theoretical sustainable tennis ball had a carbon footprint of 0.027 kg CO_2, compared to the emission of a normal ball, which is 0.58 kg CO_2, significantly lowering the environmental impact. Yet, comprehensive life-cycle assessments are necessary to understand the environmental implications fully. Future research should focus on optimizing these materials to balance performance with minimal ecological impact. Adopting sustainable materials in tennis ball manufacturing presents an interesting challenge. While natural materials can substantially reduce carbon footprints, they introduce complexities regarding resource consumption. Collaborative efforts among researchers and industry stakeholders are needed to drive the shift towards more environmentally friendly practices in the industry.

Introduction

The need for sustainable materials in the tennis ball industry is becoming increasingly important as awareness grows about the environmental impact of the tennis balls used today. About 125 million tennis balls are sold and disposed of each year in the United States alone, inducing incredible waste. Additionally, over 360 million tennis balls are produced annually on a global scale, most of which end up in landfills due to their non-recyclable materials. Tennis balls are made of primarily vulcanized rubber, a material that undergoes a chemical process where sulfur is added to natural rubber, a process done to enhance its properties. This process, however, makes this type of rubber not only non-biodegradable but also difficult to recycle, in turn causing long-term environmental impacts. Thus, the need for sustainable materials within this space is evident.

This literature review is guided by numerous objectives that are focused on the adoption of sustainable materials within the realm of the tennis ball industry. A primary goal is to recognize the environmentally friendly materials that have been proposed for use in sports equipment. Examples include options such as biodegradable rubbers derived from natural polymers and organic textiles. Along with this objective, this review also attempts to understand how the current production of tennis balls contributes to environmental degradation, and how we can solve this problem.

The scope of this literature review focuses on developments within the sustainable materials space from the last decade. Some key themes include sustainability and circular economy practices. The primary sources used in this review are journal articles that cover a wide range of subjects about the sustainable material industry. Specifically, many of the publications are about material science, where they investigate alternative materials as well as their mechanical properties. By using this research, this review aims to display the entirety of tennis balls currently, and what they may look like in the future. The significance of this review mainly lies in its contribution to the continuous efforts to move away from the environmentally harming practices of tennis ball manufacturing. It not only allows a new perspective to be uncovered but could also present solutions that could significantly decrease the environmental footprint that tennis balls bring. Furthermore, this review is necessary because it raises awareness among the manufacturers. By showing alternative resources, the manufacturers' minds can be opened, possibly even encouraging them to explore the innovations presented here.

Current Materials Used in Tennis Balls

Tennis balls primarily consist of a vulcanized rubber core and a felt cover, each giving the ball the properties to perform properly. The rubber core is made through vulcanization, a process where sulfur is added to natural rubber, increasing durability and strength. After vulcanization, this rubber core is molded into two spheres, which are combined, filled with pressurized gas, and then sealed. Finally, this core is covered with felt, the full on the outside of the ball, which is composed of a blend of wool and synthetic fibers, including how the ball bounces.

Although they may appear similar on the outside, there are various types of tennis balls, each with an intended surface and level of play. For example, extra-duty balls have a thicker feel and are better suited for rougher surfaces such as outdoor hard courts. This thick felt slows the wear of the ball, allowing it to last longer and reducing its speed over time. Regular-duty balls, on the other hand, are typically used on softer surfaces like clay and grass. They have a thinner felt layer, leading to play faster and a shorter lifespan.

While the materials used have effectively provided consistent performance for tennis players, they also bring significant environmental downsides. Although natural rubber is vulcanized, it is non-biodegradable, making it difficult to recycle or decompose. Not only this, but the felt used for tennis balls is made up of a blend of different synthetic components, once again presenting environmental troubles.

In recent years, however, there has been a greater interest in creating more environmentally friendly balls due to the general public becoming more aware of environmental hazards. Companies like Wilson and Renewaball, for example, are leading in this market currently. Wilson’s Triniti balls contain a new rubber core that does not need pressurization and is packed in biodegradable materials. Renewaball focuses on recycling used tennis balls to create new ones, resulting in a product with a 29% lower carbon footprint than standard balls. These developments display a shift in the industry towards sustainability, promoting the need to explore alternative materials.

Sustainable Alternatives for Tennis Ball Manufacturing

Natural Rubber Alternatives

The first thing that must be replaced in a tennis ball to make it eco-friendly would be its core, which is currently made up of vulcanized rubber. As a start, rubber in its natural form is biodegradable, leading to an exploration of natural rubber as a replacement. Specifically, three types of rubber are derived from the plants hevea (Hevea brasiliensis), guayule (Parthenium argentatum), and Russian dandelion (Taraxacum kok-saghyz). These plants offer sources of natural rubber that could remove a tennis ball’s reliance on its current vulcanized rubber.

Hevea Rubber

Hevea rubber, derived from the Hevea brasiliensis tree, remains the world’s most extensively used natural rubber due to its exceptional mechanical properties. One of the critical features of Hevea rubber is strain-induced crystallization, a process in which its molecular chains align under stress, forming crystalline structures that give the material strength

(Ikeda et al., 2016). This phenomenon is needed for applications like tire manufacturing, where Hevea rubber's ability to withstand dynamic stresses makes it a great material choice.

Strain-induced crystallization also allows Hevea rubber to have incredibly high durability, possibly suitable for loading conditions such as vibration dampers and seismic bearings in buildings. The crystallization process, triggered when the material is stretched beyond a specific threshold, increases tear resistance. Hevea rubber's elasticity results from its poly(1,4-cis-isoprene) structure, which exhibits high stereoregularity, making it able to maintain its performance under repeated stress (Ikeda et al., 2016).

From a sustainability perspective, Hevea rubber offers several environmental advantages as a renewable resource. Latex is harvested through tapping, which does not harm the tree and allows for continuous production for several decades. The trees typically begin producing latex after seven years of growth and are usually replanted every 25-30 years (Soratana et al., 2017). Furthermore, rubber plantations contribute positively to the environment by acting as carbon sinks, capturing carbon dioxide from the atmosphere. However, the expansion of rubber plantations, particularly in Southeast Asia, has raised concerns about deforestation and biodiversity loss, demonstrating a need to pay attention to where the trees are planted.

Efforts to enhance Hevea rubber's sustainability have led to significant advances in breeding programs, aiming to improve yield, disease resistance, and tolerance to environmental stresses such as drought and tapping panel dryness. Molecular biology has facilitated the identification of key genes involved in rubber biosynthesis, including CPT, CPTL, REF, and SRPP, opening possibilities for genetic manipulation to increase latex production and combat the challenge of gene erosion (Men et al., 2019).

One of the challenges facing the Hevea rubber industry is the crop's susceptibility to diseases, which can significantly reduce production (Cornish, 2017). Additionally, the high protein content in Hevea rubber can trigger allergic reactions in sensitive individuals, limiting its use in certain medical applications. The protein content, which includes allergenic proteins, distinguishes Hevea rubber from alternatives like guayule rubber, which is hypoallergenic (Venkatachalam et al., 2013).

In terms of processing, Hevea rubber extraction relies on adding ammonia (NH3) to prevent coagulation before the latex reaches the mill. The rubber processing industry in Indonesia, a major producer of Hevea rubber, primarily uses electricity generated from coal (44%), natural gas (31%), and oil (13%), with a smaller contribution from hydropower (7%), geothermal (5%), and renewables (1%) (Soratana et al., 2017). In addition to rubber, Hevea processing generates valuable by-products such as rubberwood residues and seed oil, which can produce electricity and biodiesel, respectively.

Looking to the future, expanding the genetic base of Hevea brasiliensis is necessary to expand the sustainability of the global rubber supply. Research efforts focus on improving the Hevea tree through biotechnology and genetic engineering and exploring other rubber sources like guayule and Russian dandelion.

Russian Dandelion Rubber

Russian dandelion (Taraxacum kok-saghyz) also appears to be a viable alternative source of natural rubber. This plant produces rubber in specialized cells known as laticifers, primarily in its roots. The rubber content in Russian dandelion roots has been found to range from 4% to 5% in wild specimens, and breeding efforts have led to increases in rubber yield over successive cycles of selection. A specific example showed that after four breeding cycles, the rubber content in Russian dandelion reached 6.4% of the plant's dry weight, with some anomalies showing as much as 14.6% rubber content (Hodgson-Kratky et al., 2017). This increase in yield shows the potential for further optimization.

In addition to its promising rubber content, Russian dandelion rubber possesses mechanical properties comparable to Hevea rubber, making it suitable for demanding applications like tire manufacturing. One of the notable advantages of Russian dandelion is its ability to grow in temperate climates, which expands the geographical range of rubber production beyond the tropical regions where Hevea brasiliensis is traditionally grown. This diversifies global rubber sources and reduces transportation emissions associated with long-distance rubber shipping. Russian dandelion's growth cycle is relatively rapid, as it is an annual plant, and planting densities of around 200,000 plants per hectare

are recommended for optimal rubber production. The best cultivation fields in the United States have reported rubber yields of approximately 110 kg per hectare, while yields in Russia have reached as high as 200 kg per hectare (Cornish, 2017).

From a sustainability perspective, Russian dandelion offers several advantages. It can be cultivated on marginal lands unsuitable for food crops, thereby minimizing competition with agricultural production. Additionally, its capacity to thrive in non-tropical environments reduces the need for water-intensive irrigation, often required for Hevea plantations in tropical regions. This characteristic makes Russian dandelion an attractive crop for regions facing water scarcity or seeking to implement more sustainable land-use practices.

However, some challenges remain. One potential issue is that Russian dandelion rubber particles may contain more associated proteins than Hevea rubber ones. This raises concerns about the potential for allergic reactions in individuals already sensitized to Hevea's natural rubber. Further research is needed to assess the allergenic properties of Russian dandelion rubber and ensure its safety for widespread use, particularly in medical applications.

Despite these challenges, Russian dandelion represents a promising alternative to Hevea rubber, offering comparable mechanical properties, a wider cultivation range, and more sustainable production practices. Ongoing breeding programs focus on increasing rubber yields and optimizing the plant's performance under various environmental conditions.

Guayule Rubber

Guayule (Parthenium argentatum), a shrub native to the arid regions of the southwestern United States and northern Mexico, also appears to be a promising alternative rubber source, seeming as a more sustainable and hypoallergenic substitute to traditional Hevea rubber. The rubber content of guayule varies between 3-12% by dry weight, depending on the plant’s age and growing conditions (Cornish, 2017). Its ability to thrive in semi-arid regions with minimal water and its cultivation on marginal lands make guayule a viable option for sustainable agriculture. Guayule's water requirement is notably lower than that of Hevea, at around 2,850 mm biannually, offering significant water savings in areas where water scarcity is a concern (Soratana et al., 2017).

From a chemical perspective, guayule rubber boasts a high molecular weight of approximately 1,280 kDa, comparable to that of Hevea rubber. Mechanically, guayule rubber, as well as both Hevea and Russian Dandelion, also exhibits strain-induced crystallization when cross-linked with sulfur, enhancing its performance under repeated stress (Venkatachalam et al., 2013). Guayule rubber has a lower modulus compared to Hevea rubber, resulting in a softer material, but it still offers high tensile strength and elasticity, making it ideal for applications requiring both flexibility and durability. Additionally, guayule rubber is less prone to storage hardening and is considered more stable for long-term storage compared to Hevea rubber. However, it is less stable to oxygen and heat, undergoing irreversible heat-induced chain cleavage, possibly affecting performance.

In terms of environmental impact, guayule rubber production shows promise. Guayule rubber exhibits lower ozone depletion potential, global warming potential, and acidification potential compared to both Hevea and synthetic rubber. Guayule’s cultivation also has less impact on deforestation and biodiversity loss, as it can be grown on non-arable land unsuitable for food crops, reducing competition for agricultural resources.

In summary, guayule rubber represents a promising alternative to Hevea rubber, both in terms of its mechanical properties and its environmental benefits. Its ability to grow in water-scarce regions, hypoallergenic nature, and lower environmental footprint make it an attractive option for industries looking to reduce their reliance on traditional rubber sources. As research continues, guayule could significantly meet the growing global demand for natural rubber while minimizing ecological impacts.

Biodegradable Polymers

Another potential replacement for the core of a tennis ball lies in biodegradable polymers, particularly polylactic acid (PLA) and polyhydroxyalkanoates (PHAs). These materials, derived from renewable resources such as cornstarch, sugarcane, and microbial fermentation, offer an eco-friendly alternative to traditional synthetic polymers.

Polylactic Acid (PLA)

Polylactic acid (PLA) is a biodegradable thermoplastic polyester made from renewable resources, such as cornstarch and sugarcane. PLA exhibits good mechanical properties, making it an attractive alternative to conventional petroleum-based plastics. For example, PLA's tensile strength ranges between 21 and 60 MPa, and Young's modulus can vary from 0.35 to 3.8 GPa, depending on its formulation. Pure poly-L-lactic acid (PLLA) has been reported to have a tensile strength of approximately 59 MPa and Young's modulus around 3.8 GPa, comparable to traditional plastics such as polyethylene terephthalate (PET) and polystyrene (PS). Despite its rigidity, PLA has a relatively low elongation at break (2.5–7%) and poor impact resistance, which limits its use in applications that require flexibility and toughness (Ranakoti et al., 2022).

Various strategies have been explored to enhance PLA's mechanical performance. Blending PLA with other polymers, such as polyhydroxybutyrate (PHB), and adding reinforcements, such as talc or kaolin, have improved its tensile properties and modulus of elasticity. For instance, a study found that blending PLA with 25 wt% PHB significantly improved the blend's tensile strength. Similarly, PLA/talc composites exhibit better stiffness than PLA/kaolin composites, owing to earlier crystallization in the former (Naser et al., 2021a).

PLA's applications span a wide range of industries due to its biodegradable and bio-based nature. In the packaging industry, PLA is used for products such as bottles, films, and disposable tableware. Its biodegradability makes it an attractive option for reducing plastic waste, as it can break down into carbon dioxide, water, and biomass under industrial composting conditions. PLA's biocompatibility also makes it suitable for biomedical applications like sutures, drug delivery systems, and tissue scaffolds, where it degrades harmlessly in the body. Furthermore, PLA is a popular filament material in 3D printing, where its low melting temperature and ease of processing are advantageous.

Despite these advantages, PLA has limitations, particularly in terms of biodegradation in natural environments. While it degrades relatively quickly under industrial composting conditions, it requires high temperatures and humidity to do so, and its degradation in natural settings is much slower. Additionally, the production of PLA from crops such as corn and sugarcane raises concerns about land use and the environmental impact of large-scale agriculture. For example, PLA production is energy-intensive, though it still consumes significantly less energy over its life cycle compared to petroleum-based plastics like polypropylene (PP) and PET. One study suggests that replacing PET with PLA could reduce primary energy demand by 40%, making it a more sustainable alternative (Mosomi et al., 2024).

The versatility and sustainability of PLA are driving its adoption across various sectors, though continued research into improving its mechanical properties and environmental impact is needed for it to reach its full potential.

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) are a diverse family of biodegradable polyesters synthesized by various microorganisms through fermentation, often using renewable feedstocks like sugar and starch. PHAs are classified into two types: short-chain-length PHAs (scl-PHAs), such as polyhydroxybutyrate (PHB), and medium-chain-length PHAs (mcl-PHAs). PHB, the most common scl-PHA, is characterized by its stiffness and brittleness, with a tensile strength of around 40 MPa and a tensile modulus of 1.7–3.5 GPa. However, PHB's low elongation at break (3.0–6.0%) makes it less suitable for applications requiring flexibility. To address this limitation, copolymers like polyhydroxybutyrate-co-hydroxyvalerate (PHBV) are developed by introducing hydroxyvalerate units, which enhance flexibility and toughness but reduce tensile strength slightly to around 30–38 MPa (Naser et al., 2021b).

The mechanical properties of PHAs can vary significantly based on their composition. For example, PHBV's elongation at break (20%) is much higher than that of PHB, which improves its impact resistance. The flexibility of PHAs can be tailored for specific applications by modifying the monomer ratios, blending PHAs with other polymers, or adding plasticizers. Blending PHAs with polymers like polylactic acid (PLA) can substantially improve mechanical properties. For instance, a 75/25 wt.% PLA/PHB blend demonstrates improved tensile strength compared to neat PLA. These modifications also help overcome some of the processing challenges PHAs face, such as slow crystallization rates and thermal instability during melting, which can cause degradation if not managed properly (Naser et al., 2021b).

PHAs are particularly valued in industries where biodegradability is critical. In the medical sector, they are used for sutures, bone plates, wound dressings, and drug delivery systems due to their biocompatibility and ability to degrade harmlessly within the human body. PHAs also find applications in food packaging, disposable products, and agricultural films, offering a biodegradable alternative to petroleum-based plastics, like PLA. PHBHx, for example, shows 35% biodegradation after 28 days in seawater, showing PHAs' potential to reduce plastic waste in marine environments (Atiwesh et al., 2021).

The sustainability of PHAs is a key advantage, as they are produced from renewable resources through microbial fermentation. Organisms like Cupriavidus necator can accumulate up to 80% of their dry mass as PHB when fed substrates like glucose. Production processes for PHAs can be optimized using waste materials or non-food biomass, which makes PHA production more environmentally friendly. However, challenges remain, such as the high costs associated with production and the energy-intensive nature of PHA synthesis. For example, PHA/PLA blends involve energy-intensive processes during fiber extrusion. Despite this, PHAs' ability to degrade in various environments, including soil and water, reduces their long-term environmental impact compared to traditional plastics (Fernandez-Bunster & Pavez, 2022).

Globally, companies are working to scale up PHA production to meet increasing demand. For instance, Tianjin Green Bioscience in China produces 10,000 tons of P3HB4HB annually, which is used in applications ranging from raw materials for packaging to disposable items (Naser et al., 2021b). However, PHA production is still relatively expensive compared to petroleum-based plastics, limiting its widespread commercial adoption. Nonetheless, ongoing research aims to reduce production costs and improve the mechanical properties of PHAs, allowing for widespread PHA use.

Organic Textiles for Felt Covering

A potential replacement for the felt of a tennis ball lies in natural fibers, particularly hemp, and flax. These fibers, derived from renewable and biodegradable plant sources, offer an eco-friendly alternative to synthetic materials like nylon and polyester. Known for their high tensile strength and durability, hemp and flax fibers present a sustainable option that can maintain the performance characteristics of tennis ball felt while reducing reliance on petroleum-based materials.

Hemp Fibers

Hemp fibers are highly regarded for their outstanding mechanical properties, which make them an excellent material for use in industrial applications. The tensile strength of hemp fibers typically ranges from 550 to 900 MPa, with an average tensile strength of 857 MPa at optimum harvest times, showcasing their incredible strength. The Young's modulus of hemp fibers, which measures stiffness, ranges between 58 and 80 GPa, also indicating a high rigidity. This spectacular strength is likely the result of the physical structure of hemp fibers. These fibers are located in the bast (phloem) of the hemp plant and have a multicellular structure with numerous lumens arranged side by side. Each fiber's cell wall consists of multiple layers, with a primary wall and a secondary wall made up of three distinct layers (S1-S3). The typical fiber length spans from 5 to 55 mm, and with a density of approximately 1.5 g/cm³, hemp fibers are ideal for spinning into yarns (Manaia et al., 2019).

When looking into composite materials, hemp fibers displayed an impressive improvement in mechanical properties. For example, composites that contain 30% hemp fiber content exhibit tensile strengths of up to 60 MPa and flexural strengths as high as 100 MPa. Additionally, the impact strength of these composites can reach up to 25 kJ/m², depending on the fiber orientation and matrix used. However, hemp fibers are hydrophilic, meaning they tend to absorb moisture, which can negatively affect their performance in composite materials. To mitigate this, surface treatments such as alkali and silane treatments are employed to improve interfacial adhesion between the hemp fibers and the matrices, improving their durability (Manaia et al., 2019).

Hemp fibers are increasingly being used in a variety of industries, with the automotive industry leading the way. Hemp fiber composites are used in the production of lightweight, durable interior components such as door panels, dashboards, and trunk liners due to their high strength-to-weight ratio. The construction industry also makes use of hemp fibers in products like insulation materials, fiberboards, and hempcrete—a combination of hemp hurds and lime that provides improved thermal and mechanical properties. Additionally, the textiles industry takes advantage of hemp fibers' durability, breathability, and antimicrobial properties to produce fabrics for clothing, upholstery, and home furnishings. In fact, hemp fabrics can even block up to 95% of ultraviolet rays, making them great for outdoor or protective wear (Ahmed et al., 2022).

The sustainability of hemp fibers is another significant benefit. Hemp is a fast-growing plant that requires minimal pesticide or herbicide use, and its deep root system helps prevent soil erosion while improving soil health. A typical seed rate for hemp cultivation is 50 kg/ha, and the plant can be harvested after just four months of growth (Seile et al., 2022). Hemp can be grown without the need for pesticides or herbicides, as it is naturally resistant to rodents, fungi, and many types of weeds. Its cultivation requires far less water than other fiber crops, such as cotton, making it an environmentally friendly alternative for fiber production. Notably, hemp can be grown in various climates, further reducing the environmental footprint of its cultivation. Given its incredible properties and environmental benefits, as research and development into hemp processing techniques continue, the material's potential applications to sustainable industries will only expand.

Flax Fibers

Flax fibers possess remarkable mechanical properties, making them a highly sought-after material in the composite industry. Their tensile modulus ranges from 30 to 70 GPa, while tensile strength varies from 200 to 1,000 MPa, depending on the quality, fiber orientation, and volume fraction. The flexural modulus of flax composites can reach values between 6 and 30 GPa, and flexural strength ranges from 50 to 300 MPa. In comparison to other natural fibers, flax is one of the strongest organic fibers, surpassing cotton in tensile strength, which is up to two or three times higher. The maximum tensile strength of flax can reach up to 1,500 MPa, and its elongation at break is 3.2%. These properties enable flax fibers to reinforce materials used in high-performance applications across different sectors (Rahman, 2021).

Flax fiber-reinforced composites are increasingly being used in industries such as automotive, construction, and sports equipment. In the automotive sector, flax composites offer weight reduction while maintaining structural integrity, which is why they are used for interior panels, door trims, and dashboard components. The sports industry incorporates flax into products like bicycles and surfboards due to its stiffness-to-weight ratio and natural damping properties. In construction, flax fibers are utilized in insulation materials and composite panels, contributing to more sustainable building practices. The ability of flax fibers to improve mechanical performance while reducing environmental impact makes them a great choice in many technical applications (Rahman, 2021).

Flax cultivation and processing also highlight its sustainability. The cultivation of flax contributes to soil health through crop rotation and requires relatively low inputs of water, fertilizers, and pesticides, making it environmentally friendly compared to other fiber crops like cotton. For instance, flax requires three times less water to grow than cotton fibers. One hectare of flax cultivation contributes to the sequestration of 3.7 tonnes of CO_2, making it a carbon-negative crop. Additionally, flax fibers are biodegradable and recyclable, reducing the overall environmental impact of products made from this material (Seile et al., 2022).

From a processing perspective, flax stalks yield 86.55% fibers, 13.45% shives, and a small amount of dust. The retting process, which helps separate the fibers from the stalks, results in an 11% mass loss. Flax fibers have a dry matter content of 90%, making them suitable for various processing techniques in composite materials. The energy required to produce flax fibers is also significantly lower than that of synthetic fibers, such as glass fibers. Producing flax fibers requires approximately 10 MJ/kg, compared to the 50 MJ/kg needed for glass fibers, displaying flax's energy efficiency (Seile et al., 2022). In summary, flax fibers combine impressive mechanical properties with environmental sustainability, making them a valuable material in industries that aim to reduce reliance on non-renewable, synthetic fibers.

Recycled and Composite Materials

Glass/Banana Fiber Reinforced Composites

Banana fiber-reinforced hybrid composites, particularly in sports industries like field hockey, have emerged as a promising material by combining the natural strength of banana fibers with synthetic fibers such as E-glass within an epoxy resin matrix. These composites leverage the benefits of both fiber types: banana fibers, which are derived from agricultural waste and are biodegradable, and E-glass fibers, known for their high tensile strength and durability. By integrating these materials, manufacturers achieve a balance between sustainability and mechanical performance (Al Rashid et al., 2020).

To improve the properties of banana fibers, treatments like sodium hydroxide (NaOH) are applied to remove impurities and improve the bond between the fibers and the resin matrix. This treatment increases the mechanical performance of banana fiber composites. While hybrid composites containing glass and banana fibers exhibit impressive flexural and tensile strength, increasing the proportion of banana fibers can reduce strength. This is attributed to the hydrophilic nature of banana fibers, which can weaken the bond with the matrix compared to synthetic fibers (Al Rashid et al., 2020).

Banana fiber-reinforced composites offer distinct advantages, especially in sustainability. Banana fibers are lightweight and derived from renewable sources, contributing to a reduced environmental impact by minimizing the use of synthetic fibers. The biodegradability of banana fibers means these composites contribute to less environmental waste compared to traditional materials like carbon or glass fibers.

The mechanical properties of these hybrid composites vary based on the fiber configuration and the proportion of banana to glass fibers. For instance, composites with a higher proportion of E-glass fibers (e.g., G8, consisting entirely of E-glass) exhibit higher tensile strength, ranging from 3100–3800 MPa, and a Young's modulus of 72.5–75.5 GPa. In contrast, banana fibers have a tensile strength of 392–677 MPa and a Young's modulus of 27–32 GPa. When the two materials are combined, as in the G7B1 configuration (one layer of banana fiber and seven layers of glass fibers), the composite demonstrates better flexural strength compared to an all-glass fiber composite (G8) (Al Rashid et al., 2020).

As the number of banana fiber layers increased (e.g., G6B2 with two layers of banana fibers), the overall strength of the composite decreased (Al Rashid et al., 2020). This suggests that banana fibers can be effectively used in hybrid composites, but their content must be carefully optimized to prevent a reduction in mechanical performance. In field hockey, where stiffness, durability, and reduced weight are incredibly important, these hybrid composites are ideal for equipment like hockey sticks, providing a more eco-friendly alternative to purely synthetic composites while maintaining the necessary performance standards.

Current vs. Proposed Sustainable Tennis Ball

Table 1. Proposed Composition of Sustainable Tennis Ball

Aspect	Tennis Ball with Current Materials	Theoretical Sustainable Tennis Ball
Core Composition	Synthetic Rubber (often petroleum based)	Natural Hevea Rubber (from *Hevea brasiliensis* tree)
Felt Covering	Blend of wool and nylon (a petroleum-based synthetic fiber)	Hemp fibers (renewable and biodegradable)
Carbon Footprint	0.58 kg CO2	0.027 kg CO2*
End of Life	Difficult to recycle; can take over 400 years to decompose in landfills	Biodegradable components, leading to faster decomposition and less environmental impact

*To calculate the carbon footprint of a tennis ball made with Hevea rubber for the core and hemp fiber for the felt, the known carbon footprints of the respective materials were used. Hevea rubber has a carbon footprint of 0.39 kg CO_2e per kilogram of rubber. For hemp fiber, the carbon footprint ranges between 364–406 kg CO_2e per ton (equivalent to 0.364–0.406 kg CO_2e per kilogram). Assuming that an average tennis ball weighs approximately 58 grams, of which 85% (49.3 grams) is the rubber core and 15% (8.7 grams) is the felt, the contributions from each material were calculated proportionately.

Discussion

Carbon Footprint

Hemp and flax fibers have been identified as environmentally favorable alternatives to traditional glass fibers due to their significantly lower carbon footprints. Hemp fiber production results in a carbon footprint ranging from 364 to 406 kg CO_2 equivalent per ton, while flax fiber production stands at approximately 349 kg CO_2 equivalent per ton. In contrast, glass fiber production is associated with a carbon footprint between 1.8 to 4.6 tons CO_2 equivalent per ton. This substantial difference highlights the potential for hemp and flax fibers to reduce greenhouse gas emissions when used in composite materials (Seile et al., 2022).

The incorporation of hemp fibers into non-woven materials contributes to a negative global warming potential, effectively reducing the overall environmental impact. Specifically, the use of hemp leads to a 43% reduction in global warming potential compared to other components within these materials. This significant decrease is attributed to the carbon sequestration capabilities of hemp during its growth cycle, where it absorbs more CO_2 than is emitted during processing (Seile et al., 2022).

Blending natural fibers with biodegradable polymers further enhances environmental benefits. Composites made from flax and polylactic acid (PLA) fibers exhibit a carbon footprint of 1.19 kg CO_2 per kg of composite, which is an 87% reduction compared to composites made from polyamide 66 reinforced with glass fibers (PA66/GF) (Seile et al., 2022). Similarly, hemp/PLA composites demonstrate an 81% smaller carbon footprint than PA66/GF composites. These findings underscore the environmental advantages of using natural fiber-reinforced biopolymers over traditional petroleum-based composites.

Comparatively, the carbon footprint of cotton fibers ranges from 0.5 to 4 kg CO_2 equivalent per kg, which can be up to four times higher than that of flax fibers, measured between 0 to 0.8 kg CO_2 equivalent per kg. This disparity emphasizes the importance of selecting low-impact natural fibers like flax to minimize carbon emissions in material production (Stavropoulos et al., 2023).

Analysis

The production processes of biodegradable polymers like PLA can be resource-intensive and environmentally burdensome despite the end-of-life benefits of biodegradability. In the rubber industry, particularly with Hevea rubber, there are significant environmental challenges related to deforestation, land use change, and biodiversity loss.

Advancements in end-of-life management technologies, such as recycling and reuse strategies, are important for mitigating the environmental impacts of rubber products. Additionally, promoting the use of rubber wood and natural rubber as alternatives to non-renewable materials can contribute to resource conservation and emission reductions. A shift towards sustainable practices in the rubber industry necessitates collaborative efforts involving technological innovation, supportive policy frameworks, and engagement with farmers and local communities. Emphasizing sustainability throughout the value chain can lead to significant environmental benefits while also supporting economic development.

Conclusion

In summary, the use of natural fibers such as hemp and flax in composite materials offers significant reductions in carbon footprint compared to traditional glass fibers, contributing to lower greenhouse gas emissions. However, these environmental benefits are counterbalanced by increased water footprints and energy consumption associated with the cultivation and processing of natural fibers. The production of biodegradable polymers like PLA, while offering end-of-life advantages, is energy-intensive and contributes substantially to environmental toxicity categories.

The environmental impact of materials is complex, requiring a life cycle perspective to fully understand the trade-offs involved. Sustainable material selection for applications like tennis ball manufacturing should consider not only the carbon footprint but also water usage, energy consumption, resource depletion, and potential impacts on biodiversity and land use.

Future research should aim to fill the data gaps identified, particularly concerning emerging materials like PHA and alternative natural rubbers, to enable a more comprehensive sustainability assessment. Collaboration among researchers and industry stakeholders is essential to develop and implement materials that minimize environmental impacts while meeting performance requirements.

Limitations

The assessment presented is subject to several limitations due to gaps in the available data. The sources primarily focus on the comparison of hemp, flax, and glass fibers within composite materials, providing limited information on other materials such as polyhydroxyalkanoates (PHA), Russian dandelion rubber, and glass/banana reinforced fibers. This restricts the ability to conduct a comprehensive evaluation of all potential sustainable materials for tennis ball manufacturing.

Detailed data on energy consumption and non-renewable resource depletion for many of the listed materials still need to be included. The absence of specific information on these aspects makes it challenging to compare materials accurately and to identify the most sustainable options comprehensively. Additionally, some of the data referenced, particularly regarding water footprints, are based on studies from the late 1990s to early 2000s. Agricultural practices, technological advancements, and improvements in resource efficiency since then may have altered the environmental profiles of these materials.

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