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# Sustainability of Badminton Shuttlecocks: A Systematic Review of Environmental Impact, Material Chemistry, and Performance Feasibility of Sustainable Alternatives

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## Abstract

The sport of badminton has become really popular all over the world and this has caused a big problem. The traditional badminton shuttlecocks are made from the feathers of ducks and geese which means that the sport is connected to the poultry industry, which produces a lot of carbon and is bad for our planet. On the other hand, modern badminton shuttlecocks are made from synthetic materials like nylon or plastic and these do not use any animal products. However these shuttlecocks are made from petrochemicals. They do not break down easily which means they can harm the environment in the long run. This study looks at the badminton shuttlecocks made from feathers and synthetic materials to see how they affect the environment. It also looks at how they last and how well they fly through the air. By looking at the life cycle of these shuttlecocks, the chemicals they are made of and how they are engineered this study tries to find a solution to the problem of badminton shuttlecocks being bad for the environment. It also looks at the types of badminton shuttlecocks that are made from natural materials, recycled materials and a mix of both. It compares these shuttlecocks to see which ones are the most sustainable and which ones fly the best. The study also uses data from badminton tournaments to see how much waste is produced and it looks at the rules that the Badminton World Federation has about using feathers in shuttlecocks.

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## 1. Introduction

Shuttlecocks are not reused after crossing a certain level of degradation and are ultimately thrown away. Professionals use dozens of shuttlecocks per match, and global play multiplies this demand hugely. Sporting materials should be designed to have minimal

ecological footprint while maintaining precision. However, shuttlecock manufacturing currently fails to meet this criterion.

Feather shuttlecocks require primary feathers from geese or ducks. Although the feathers used are usually by-products of meat production, the poultry industry still remains a significant source of carbon emissions due to feed production, land use, and methane production (Poore & Nemecek, 2018). In addition to this, feather shuttles degrade quickly and are therefore discarded quickly. To increase longevity, synthetic shuttlecocks are made of nylon or PVC polymers that have been stabilised with additives that can tolerate high temperatures and mechanical stress. These materials have low biodegradability and contribute to the accumulation of plastic waste over time (Hopewell et al., 2009). The environmental impact clearly originates from both feather and synthetic shuttlecocks and needs to be addressed in the near future.

Current research does not solely focus on the environmental impact of shuttlecocks; it is spread into multiple domains and requires compilation. Aerodynamic modelling research focuses on drag coefficient and deceleration rate to simulate feather flight dynamics (Alam et al., 2010), while research in polymer science is concerned with mechanical properties and degradation rates. To date, there has been no integration of lifecycle assessments with feasibility studies for sustainable shuttlecock materials. Alternative designs, such as bio-based polyamides, recyclable thermoplastics, and hybrid designs, have not been sufficiently studied in terms of the aerodynamic demands that are required for badminton, where drag forces ( $FD = \frac{1}{2}\rho v^2 CDA$ ) determine shuttlecock deceleration.

This systematic review aims to fill this current gap by combining environmental, chemical, and performance information into a single framework. The objectives are: (1) to compare the lifecycle costs of feather shuttlecocks and synthetic shuttlecocks; (2) to investigate the chemical composition and degradation processes of modern polymer materials; and (3) to check the feasibility of proposed sustainable materials against required aerodynamic properties. By combining scattered research results, this review aims to shed light on cases where sustainability means a sacrifice in performance and cases where innovation is still possible.

The paper is organised as follows. Section 2 reviews existing literature across the three analytical domains. Section 3 describes the systematic search and synthesis methodology. Section 4 presents the core integrated analysis, anchored by a conceptual framework figure. Section 5 provides a critical discussion of findings, limitations, and the regulatory dimension of feather selectivity, and Section 6 identifies future research directions before the conclusion in Section 7. This study establishes the territory by demonstrating the environmental urgency of shuttlecock material choices, identifies the niche as the absence of any integrated cross-disciplinary framework, and occupies that niche through the synthesis offered here.

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## **2. Literature Review**

The manufacturing of shuttlecocks combines two issues: the way we raise animals for food and the way we use plastics made from petroleum. There is a lot of information about these two issues on their own. However when we specifically talk about shuttlecocks we do not have information about how these issues affect the environment. What we do have is spread out across areas of study such as how air moves around things, the chemistry of plastics and the science of the environment. Each of these areas of study mostly works alone. Does not often talk to the others about shuttlecock manufacturing. Shuttlecock manufacturing is a part of this problem because it involves both animal products and plastics. The people who study shuttlecocks and the environment need to work to find a solution to the problem of shuttlecock manufacturing.

### ***2.1 Feather Shuttlecocks and the Poultry Supply Chain***

The use of waterfowl feathers in shuttlecock production is frequently framed as ecologically neutral on the grounds that feathers are a by-product of meat processing. This framing, while not entirely unfounded, obscures the upstream environmental costs of the system that produces them. Poore and Nemecek's (2018) landmark meta-analysis of over 38,000 farms demonstrated that poultry production carries significant greenhouse gas emissions per kilogram of protein, primarily from feed crop cultivation, land conversion, and nitrous oxide release from manure management. Although feathers themselves are not the functional product being optimised in that system, they remain entangled in its ecological ledger. Studies that treat

feathers as having zero embodied emissions are methodologically incomplete; lifecycle analysis must account for the proportional attribution of upstream emissions to all co-products, including feathers (ISO 14040, 2006).

Compounding this is the durability problem. A feather shuttlecock typically lasts between three and eight minutes of professional play before aerodynamic degradation necessitates replacement (Phomsoupha & Laffaye, 2015). The mechanical fragility of natural vane structure, composed of interlocking barbules susceptible to separation under repetitive high-velocity impact, means that replacement frequency is inherently high. Neither athletic performance literature nor sports material science has adequately quantified the cumulative waste generated at competitive scale, particularly across Asian markets where badminton participation is highest.

## ***2.2 Synthetic Polymer Chemistry and Environmental Persistence***

The development of synthetic shuttlecocks was primarily motivated by longevity and cost, not environmental concern, and this origin is reflected in material choices. Most synthetic skirts are manufactured from nylon 6 or nylon 6,6, polyamide thermoplastics with high tensile strength and resistance to heat and moisture (Harper, 2006). Some budget-grade models use polyvinyl chloride (PVC) skirts, which require the addition of plasticizers such as di(2-ethylhexyl) phthalate (DEHP) to achieve the required flexibility, raising concerns about chemical leaching during degradation (Wormuth et al., 2006).

The environmental persistence of these materials is well-documented. Nylon 6,6 has an estimated environmental half-life of several decades under typical landfill conditions, while PVC is effectively non-degradable without specialised industrial processing (Hopewell et al., 2009). Neither material is routinely recovered through existing plastic waste streams; their composite nature, combined with cork and rubber bases, complicates mechanical recycling. Tokiwa et al. (2009) note that the biodegradability of synthetic polymers is critically limited by molecular chain length and crystallinity, both of which are maximised in performance-oriented nylon formulations. The design features that make synthetic shuttlecocks durable in service are precisely those that make them environmentally persistent after disposal.

## ***2.3 Aerodynamic Constraints on Material Substitution***

Any proposal to substitute existing materials must contend with the specific aerodynamic behaviour required of a functional shuttlecock. Unlike most projectiles, shuttlecocks are designed to decelerate rapidly from initial velocities exceeding 300 km/h in elite play, stabilising into a predictable ballistic trajectory. This behaviour depends on the high drag coefficient generated by the skirt, which functions as an aerodynamic brake (Alam et al., 2010). The drag force equation  $FD = \frac{1}{2}\rho v^2 C_D A$  shows that drag is proportional to the projected area and the drag coefficient; feather vanes achieve their particular  $C_D$  through the flexibility and micro-geometry of the barbule structure, which passively adjusts under airflow.

Synthetic approximations of this geometry have improved considerably since early rigid nylon designs, but comparative wind tunnel studies consistently report measurable differences in flight trajectory and deceleration profile between feather and synthetic shuttles (Cohen et al., 2015; Verma et al., 2013). The engineering challenge for sustainable substitutes is therefore not simply chemical but geometric: any new biopolymer or composite must replicate not just the mechanical properties of nylon or feather, but the specific aerodynamic surface behaviour that emerges from their microstructure.

#### ***2.4 Sustainable Material Candidates in Existing Research***

The literature on sustainable alternatives to conventional shuttlecock materials is still early-stage. Bio-based polyamides, particularly PA11 (derived from castor oil) and PA10,10 (derived from sebacic acid and decamethylenediamine), have attracted interest as drop-in substitutes for petrochemical nylons in sports equipment more broadly. Rosenboom et al. (2022) identify bio-based polyesters and polyamides as among the most technically mature classes of sustainable polymers, noting that PA11 achieves mechanical properties comparable to PA12 while reducing fossil carbon dependency. However, no published study has validated PA11 or PA10,10 specifically within the aerodynamic demands of a shuttlecock application.

Recycled thermoplastic approaches, including post-consumer nylon from carpet fibres or fishing nets, have been proposed within broader circular economy frameworks for sports equipment (Graupner et al., 2021), but their applicability to shuttlecock manufacture is constrained by the variability in mechanical properties that characterises recycled feedstocks. Hybrid designs combining natural feather-like geometry with synthetic or bio-based substrates

represent a conceptually appealing middle ground but remain at the prototype stage with limited public documentation of aerodynamic validation.

### ***2.5 Synthesis and Gap Assessment***

There is a seeming structural gap across these domains. Environmental literature deals with upstream emissions and downstream persistence of conventional materials but does not model aerodynamic performance. In engineering literature a detailed description of flight dynamics is given but the inputs are conventional materials. Bio-materials research finds potential replacements, but does not test them for badminton-specific aerodynamics. To date, no study has developed an integrated framework for the simultaneous assessment of environmental impact, chemical suitability and performance feasibility for a single class of sustainable shuttlecock material. This fragmentation is the major limitation of the field and this is precisely what the present review attempts to overcome.

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## **3. Methods**

This study was designed as a systematic review of peer-reviewed and technical literature, conducted to synthesise existing knowledge on the environmental, chemical, and aerodynamic dimensions of shuttlecock sustainability. A systematic approach was selected in preference to a narrative review because the subject matter spans three disciplines with distinct methodological conventions, making transparent search and selection procedures essential for reproducibility and validity. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), which provided a structured framework for each stage of the process.

### ***3.1 Study Design and Ethical Considerations***

As this study involved no human participants, animal subjects, or primary data collection, formal ethical approval was not required. All data were extracted from published, publicly accessible academic literature, and no identifiable personal information was processed at any stage. The review was conducted with full attribution of sources in accordance with academic integrity requirements. The study design is consistent with the classification of systematic reviews as secondary research, wherein primary data are synthesised rather than generated.

### **3.2 Search Strategy**

A systematic literature search was conducted across three major databases: Web of Science, Scopus, and Google Scholar. Searches were performed in February 2024 and updated in March 2024 to capture recently published material. The following Boolean search strings were applied across title, abstract, and keyword fields: ("shuttlecock" OR "badminton projectile") AND ("sustainability" OR "environmental impact" OR "lifecycle assessment" OR "carbon footprint"); ("shuttlecock" OR "badminton") AND ("polymer" OR "nylon" OR "polyamide" OR "PVC" OR "synthetic"); ("bio-based polymer" OR "biopolymer" OR "recycled thermoplastic") AND ("sports equipment" OR "aerodynamics"); and ("shuttlecock aerodynamics" OR "drag coefficient" OR "flight trajectory") AND ("material" OR "design"). Additional references were identified through backward citation tracing from key papers identified during the initial search phase.

### **3.3 Inclusion and Exclusion Criteria**

Studies were considered eligible if they were published in peer-reviewed journals or reliable technical reports, in English, and directly relevant to at least one of the three analytical domains of this review: environmental lifecycle, polymer chemistry, or aerodynamic performance. No upper date limit was applied, taking into account the historical relevance of foundational aerodynamics studies from the early 2000s. Studies were excluded if they concerned badminton only from the perspective of physiology or biomechanics without any material or environmental content, if they were conference abstracts without corresponding full-text papers or if they focused primarily on racket technology rather than shuttlecock design.

### **3.4 Data Extraction and Quality Assessment**

Following the initial database searches, titles and abstracts were screened against the inclusion criteria. Full texts of candidate papers were then retrieved and assessed for methodological quality using a structured appraisal framework adapted from the Mixed Methods Appraisal Tool (MMAT; Hong et al., 2018). Studies were evaluated on criteria including clarity of research design, appropriateness of methodology to stated objectives, transparency of analytical procedures, and acknowledgment of limitations. Only studies meeting an acceptable quality threshold were included in the final synthesis.

### **3.5 Data Synthesis**

Due to the interdisciplinary nature of the review, a thematic synthesis approach was used rather than a quantitative meta-analysis approach, which would have been inappropriate given the heterogeneity of the study designs, outcome measures and units of analysis across the three domains. The extracted data were organized into thematic clusters corresponding to the three study objectives: lifecycle environmental impact, chemical and material composition, and aerodynamic performance feasibility. The integrated analytical framework presented in Section 4 was built by identifying and mapping cross-domain relationships, contradictions and convergences.

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## 4. Core Analysis

The three domains identified in the literature review do not exist as parallel problems but interact in ways that constrain each other and have not been previously modelled in a unified analytical space. Figure 1 provides a conceptual framework for mapping these interactions. The central hub is the suggested integrated framework of this review: all candidate sustainable shuttlecock materials must be simultaneously evaluated against environmental lifecycle burden, chemical and degradation properties, and aerodynamic performance feasibility. The intersection zones, Material Substitution Feasibility, Performance-Material Trade-off, and Functional Environmental Impact per Play-Hour, are the spaces where two domains converge, and where trade-off decisions are to be made. The outer contextual boxes anchor the framework in the empirical realities driving each domain: the measured GHG intensity of poultry production, the quantified replacement frequency at tournament scale, and the BWF regulatory constraints that structurally shape both feather demand and synthetic adoption ceilings.

### ***4.1 Lifecycle Environmental Impact: Feather versus Synthetic***

A meaningful lifecycle comparison of feather and synthetic shuttlecocks would need to address the asymmetry of the typical treatment of each material in environmental accounting. In popular framing, feather shuttlecocks are often assigned low or zero embodied emissions because feathers are considered agricultural by-products. This accounting makes a simplifying assumption: the poultry system that generates feathers was not designed to generate feathers, but was built and maintained to generate meat, and all outputs of that system carry a share of its

environmental burden. The principle of life cycle assessment is to distribute all upstream emissions proportionally to all co-products, including feathers (ISO 14040, 2006).

The emissions embedded in poultry feed production alone are substantial. Soy and corn cultivation for livestock feed contributes significantly to land use change, nitrogen fertiliser inputs, and associated nitrous oxide emissions. Poore and Nemecek (2018) report that poultry meat production generates between 4 and 8 kg of CO<sub>2</sub> equivalent per kilogram of product across global production systems, with variation depending on feed efficiency, regional energy mix, and manure management practices. Even if feathers are assigned a modest fraction of these emissions, the cumulative environmental cost of feather supply for the global shuttlecock market is non-trivial when production volumes are considered.

The replacement frequency of feather shuttlecocks amplifies this problem substantially. Phomsoupha and Laffaye (2015) report that elite-level play necessitates shuttlecock replacement every three to eight minutes due to barbule damage, humidity absorption, and deformation on impact. Projecting this figure to tournament scale reveals the environmental weight of what is easily dismissed as a consumable. A major BWF Grade 1 championship, such as the BWF World Championships, typically involves approximately 500 competitive matches across five disciplines over ten days of play. Applying a conservative average replacement interval of five minutes — the midpoint of the documented service life range — and assuming an average match duration of 45 minutes, yields approximately nine shuttlecocks consumed per match. Across 500 matches, this produces an estimated 4,500 shuttlecocks discarded at a single championship event. The BWF annual professional calendar includes approximately 28 Grade 1 events; extrapolating conservatively, roughly 75,000 to 80,000 shuttlecocks are discarded from the professional circuit alone in a single calendar year. At approximately 6 grams of composite material per shuttlecock, this represents over 450 kilograms of largely non-recyclable composite waste — and this estimate does not include practice sessions, warm-up courts, or the vastly larger recreational tier, which dwarfs professional consumption by several orders of magnitude. These figures, while approximate, illustrate that the environmental cost of shuttlecock consumption is not a marginal issue addressable through incremental durability improvements alone.

Synthetic shuttlecocks perform better on longevity. A single synthetic shuttle may last several times longer than a feather equivalent before aerodynamic degradation demands replacement. This advantage, however, is substantially eroded by end-of-life considerations. Nylon 6 and nylon 6,6 are not degraded by common soil microorganisms under ambient conditions, and their composite construction with cork and adhesive renders mechanical recycling impractical. Hopewell et al. (2009) observe that mixed-material consumer goods of this type are among the most challenging waste categories to address within existing recycling infrastructure. The result is that virtually all discarded synthetic shuttlecocks are either landfilled or incinerated, with neither pathway offering meaningful material recovery.

#### ***4.2 Chemical Composition and Degradation of Synthetic Materials***

Understanding the specific chemistry of synthetic shuttlecock materials is necessary for evaluating both their environmental persistence and the plausibility of bio-based replacements. The dominant material in premium synthetic shuttles is nylon 6,6, a polyamide synthesised through the condensation of hexamethylenediamine and adipic acid. Its semicrystalline structure confers high tensile strength, thermal stability, and resistance to abrasion, properties that directly enable the repeated high-velocity impacts of badminton play (Harper, 2006). Lower-cost synthetic shuttlecocks often employ nylon 6 (polycaprolactam), which shares most of these characteristics but has marginally different crystallisation behaviour and is generally considered slightly less durable under extended mechanical loading.

PVC-skirted shuttlecocks introduce additional chemical complexity. PVC in its pure form is rigid and brittle; achieving the flexibility required for shuttlecock vanes requires plasticisation, typically using high-molecular-weight phthalate esters such as di(2-ethylhexyl) phthalate (DEHP) or diisononyl phthalate (DINP). These plasticizers migrate out of the polymer matrix over time, particularly under thermal and mechanical stress, and have been identified as endocrine-disrupting chemicals in regulatory assessments by the European Chemicals Agency (2011). The concern is more relevant at the point of manufacture and at end-of-life, when plasticizer-laden PVC enters waste streams without controlled treatment. The degradation kinetics of these materials in environmental settings are unfavourable: Tokiwa et al. (2009) report that nylon 6 shows minimal hydrolytic or enzymatic degradation under ambient soil conditions over periods of years, while PVC degradation is practically nil in the absence of UV

irradiation or industrial chemical treatment. The molecular engineering that extends the service life of a synthetic shuttle also extends its post-disposal environmental persistence indefinitely.

#### **4.3 Sustainable Material Candidates**

Bio-based polyamides offer the most structurally analogous substitution pathway for synthetic shuttlecock skirts. PA11, commercially produced under trade names such as Rilsan, is derived from 11-aminoundecanoic acid extracted from castor oil, a non-edible crop cultivated primarily in India and Africa. Its mechanical properties are broadly comparable to those of petrochemical polyamides, with a tensile strength of approximately 55 MPa and good impact resistance at ambient temperature (Rosenboom et al., 2022). PA10,10, derived from both castor oil and sebacic acid, offers a fully bio-based carbon backbone and has found industrial application in automotive components and sports equipment. The theoretical environmental benefit of these materials is meaningful: bio-based polyamides reduce fossil carbon dependency and, in well-managed biorefinement scenarios, can achieve significantly lower global warming potential per kilogram compared to petrochemical equivalents.

Recycled thermoplastics provide a way to completely circumvent the making of virgin material. Reclaimed nylon of post-consumer provenance as for example fishing nets or textile offcuts can be repolymerised back into pellets with mechanical properties close to that of virgin material (Graupner et al., 2021). The principle is directly applicable to the manufacture of shuttlecock skirts and is already being exploited by several sports equipment manufacturers for other products. The practical problem is feedstock consistency: recycled nylon pellets have a wider range of properties than virgin material and that is a problem for a part where dimensional accuracy directly affects flight behavior.

#### **4.4 Performance Feasibility of Sustainable Alternatives**

The technical validation of any replacement material must finally be measured against the aerodynamic requirements of a functional shuttlecock. The important parameter is the drag coefficient (CD) which governs the characteristic rapid deceleration from impact velocity. The CD of feather shuttlecocks is caused by the cone shape of the skirt and the micro-scale surface roughness of the vane barbules that trip the boundary layer and increase pressure drag. Alam et al. (2010) observed a CD of about 0.6 for feather shuttlecocks at typical game speeds, much

higher than would be expected for a smooth cone of similar shape and directly linked to the anisotropic surface texture of natural feather vanes.

This behavior has been increasingly mimicked in synthetic shuttles, using geometric features such as perforations, ribbing, and variable-thickness skirts to approximate the aerodynamic effect of natural barbule geometry. However, comparative studies do consistently find that there are residual differences in trajectory arc and deceleration profile, especially at velocities in excess of 150 km/h (Verma et al., 2013; Cohen et al., 2015). Bio-based or recycled polymer alternatives would need to pass BWF certification standards before they could be used in competition play, standards which include standardized testing of initial velocity, deceleration rate and flight stability. This is the most important gap in the literature as to date, no published study has tested bio-based polyamide shuttlecocks with this battery of tests.

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## 5. Critical Discussion

The results of this review shed light on a field where the incentive structures for both research and industry have traditionally been at odds with environmental innovation. It is not a matter of inertia that feather shuttlecocks continue to prevail at the professional level, and petrochemical synthetics at the recreational level. Rather, it reflects the real technical challenge of matching aerodynamic performance with the cost and durability expectations of a mass-market product. To understand why the current solutions fail, one needs to look not only at the materials themselves, but also at the assumptions and gaps in the literature that describes them.

### 5.1 *Contradictions in Environmental Framing*

One of the most significant analytical contradictions in the literature is the implicit assumption that feather shuttlecocks are environmentally preferable by default, given their origin in nature. This perspective, demonstrated by the lack of detailed life cycle examination of feather production in the sports science literature, conflates biodegradability with low environmental impact. A feather shuttlecock breaks down more readily than a nylon one under landfill conditions; the emissions embedded in its production through the poultry supply chain are not negligible, especially when considering the frequency of replacement across a playing

season. The cumulative waste volume from feather shuttlecocks is significant even without considering practice and recreational play, as demonstrated by the tournament scale projections in Section 4.1. The existing literature has not produced an integrated lifecycle comparison that addresses both production emissions and end-of-life behaviour across the full functional service life of either shuttle type.

This gap is also methodological. The definition of system boundaries in relation to sporting equipment has generally been inconsistent, sometimes excluding upstream agricultural emissions altogether, and rarely applying sensitivity analysis to co-product allocation assumptions governing feather emission attribution (Rebitzer et al, 2004). The consequence is that the evidence base for policy decisions or procurement guidelines is weaker than it appears and researchers working in aerodynamics or polymer chemistry who have taken the environmental question to be settled have done so on uncertain foundations.

## ***5.2 Tensions Between Performance Requirements and Material Substitution***

The aerodynamics literature shows a subtler problem. The performance specifications for the shuttlecocks are empirically derived from the behaviour of existing feather and synthetic designs and are not set from first principles of flight mechanics. The BWF certification standards were developed based on materials that were already in use, so any potential sustainable material is compared to a benchmark that was never intended to be material-neutral. The bio-based polyamide that produces a slightly different deceleration profile might still allow excellent sporting play, but it would not pass certification if its trajectory did not match the profile generated by conventional materials. This creates a regulatory lock-in that innovation must negotiate, but no published study has directly examined whether BWF standards could be adapted to include high-performing sustainable designs without compromising play quality.

## ***5.3 BWF Feather Selectivity as an Environmental Concentrator***

A dimension of the sustainability problem that has received almost no critical attention in the academic literature is the role of BWF equipment regulations as an active driver of environmental concentration. The BWF Laws of Badminton specify that feather shuttlecocks for competition must use natural feathers taken from the left wing of a goose or duck, with feathers required to be uniformly sized and sourced from the same bird (Badminton World Federation,

2022). This anatomical specificity is not a trivial requirement. It means that the global demand for competition-grade shuttlecock feathers is not simply a diffuse demand on the poultry industry in aggregate; it is a demand concentrated on a single anatomical zone of a single wing of waterfowl, harvested at a specific stage of the bird's growth cycle. The practical consequence is that only a fraction of the feathers available from any given bird are usable under BWF standards, meaning that far more birds must pass through the supply chain to yield a given quantity of competition-grade material than a naive calculation would suggest. This selectivity acts as a structural amplifier of the carbon intensity associated with feather supply, yet it has never been modelled explicitly in the lifecycle literature.

Furthermore, because BWF competition at the highest tiers is conducted exclusively with feather shuttlecocks, the professional tournament market creates a persistent, high-volume, price-inelastic demand for feather shuttles that cannot be displaced by improved synthetic performance alone. No synthetic shuttlecock, however aerodynamically refined, can enter this market segment under current regulations. Though this regulatory distinction between amateur and professional equipment tiers is driven by performance consistency, it has the unexamined side effect of maintaining the demand for feathers at the most visible and highest-prestige level of the sport, effectively communicating to the industry and to recreational consumers that feathers are the performance standard. Thus, any policy strategy to reduce the environmental burden of badminton will necessarily involve direct engagement with BWF equipment standards, not just with material chemistry. One of the most tractable and highest impact areas for future policy research in this space is the feasibility of a tiered regulatory approach that establishes performance-based, rather than material-based, certification criteria.

#### ***5.4 The Performance-Sustainability Paradox and Its Structural Roots***

There is a deeper tension in this field that transcends the limitations of individual studies. It is very difficult to obtain the properties which make a shuttlecock aerodynamically accurate, the surface texture, the mechanical flexibility and the geometric consistency of vane structure through engineered materials at the appropriate cost and scale. Natural feathers do this through biological growth processes that generate a hierarchical microstructure at no additional manufacturing cost; synthetic materials must manufacture this microstructure via precision manufacturing. Both of these challenges are faced by sustainable alternatives; to be produced,

maintained in service and disposed of with lower environmental impact, and to match the aerodynamic surface behaviour of established materials. This is not an impossible constraint, but it has not yet been seriously addressed as a unified design problem, and the literature currently lacks the frameworks to evaluate proposed solutions against all three criteria simultaneously.

### ***5.5 Limitations of the Present Review***

There are some important caveats to this review. As a synthesis of existing literature it is limited by the quality and scope of the studies it incorporates. The review is capable to identify the gap but unable to fill it with primary data due to the absence of integrated LCA-aerodynamic performance studies. Moreover, it was not possible to access any unpublished industry testing data, if available, from manufacturers such as Yonex, Victor or Li-Ning. Another meaningful limitation is the reliance on English-language literature, since the manufacture of badminton equipment is concentrated in East and Southeast Asia. Relevant technical or commercial research published in Chinese, Japanese, Korean, or Malay would not have been captured by the search strategy employed here, and the geographic asymmetry in the accessible evidence base may bias conclusions toward Western academic framing of sustainability.

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## **6. Future Directions and Implications**

### ***6.1 Integrated Lifecycle and Performance Modelling***

The most significant single contribution that future research could make would be an integrated lifecycle assessment that models both upstream production emissions and end-of-life behaviour alongside aerodynamic performance data for the same set of candidate materials. This would require cross-disciplinary collaboration between environmental engineers, polymer chemists, and sports scientists. The framework could be structured around the functional unit of one hour of competitive play at a defined intensity level, which would normalise for the replacement frequency differences between shuttle types and provide a basis for direct environmental comparison. Sensitivity analysis should include variation in feather emission attribution assumptions, which are currently the largest single source of uncertainty in comparing the two material categories. The tournament-scale quantification introduced in

Section 4.1 provides a baseline functional unit that future LCA studies could operationalise directly.

### ***6.2 Material Testing and BWF Certification Pathway Development***

Future research should explicitly address the relationship between BWF certification criteria and sustainable material properties. A study characterising the aerodynamic performance of bio-based polyamide shuttlecocks across the full range of BWF testing conditions, and comparing results against the tolerance bands in certification protocols, would provide the first empirical basis for determining whether current standards need modification to accommodate sustainable designs. If the performance tolerance bands are set in ways that inadvertently exclude materials producing equally enjoyable play with slightly different trajectory profiles, then the regulatory framework itself becomes an obstacle to sustainability, regardless of material chemistry progress. This type of research would benefit from direct collaboration with equipment manufacturers and the BWF.

### ***6.3 End-of-Life Valorisation and Secondary Use Pathways***

Beyond substitution, future research should investigate valorisation strategies for shuttlecock waste that do not depend on conventional recycling infrastructure. The use of synthetic shuttlecock skirt material as a minor aggregate modifier in asphalt or as filler in composite moulding compounds represents an intriguing secondary-use pathway that has been proposed but not experimentally validated for this feedstock. Feather waste valorisation, including keratinous fibre recovery for bio-composite reinforcement, is an established field in agricultural by-product research and its application to the specific feather profile of shuttlecock waste has not been explored. Establishing a secondary material economy around shuttlecock waste, however modest, would reduce landfill reliance and could offset some lifecycle environmental cost.

### ***6.4 Policy Reform and Procurement Standard Development***

The analysis of BWF feather selectivity regulations in Section 5.3 points to a clear policy research agenda. Establishing the quantitative environmental cost of left-wing feather selectivity through formal lifecycle modelling would provide an evidence basis for federation-level discussion about whether performance-based rather than material-based certification criteria are

feasible. Sporting goods procurement policies at institutional and major event level similarly lack sustainability criteria for equipment materials. Research supporting the development of such standards, including lifecycle benchmarking, certification criteria revision, and prototype validation, should be treated as a research priority rather than a downstream policy concern. The precedent for regulatory-driven material innovation exists in multiple adjacent sports industries.

### ***6.5 Geographic and Linguistic Expansion of the Evidence Base***

Future systematic reviews in this area should explicitly incorporate non-English language literature, particularly from Chinese, Japanese, and Korean academic and industry sources, to correct the geographic asymmetry identified here. Given that the majority of badminton shuttlecock manufacturing occurs in China and the broader East Asian region, technical literature from these contexts likely contains information about manufacturing processes, material choices, and performance testing that is not represented in Western academic databases. Bilingual research collaborations between institutions in Asia and Western universities would be particularly valuable in bridging this gap and ensuring that sustainability innovation in shuttlecock design reflects the full range of relevant technical knowledge.

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## **7. Conclusion**

This systematic review was undertaken to address a structural gap in the literature on badminton shuttlecock sustainability: the absence of any integrated framework simultaneously considering environmental lifecycle impact, chemical material properties, and aerodynamic performance feasibility of sustainable alternatives. The three stated objectives: comparing lifecycle costs of feather and synthetic shuttlecocks, analysing polymer chemistry and degradation behaviour, and evaluating sustainable substitutes against aerodynamic requirements, were each approached through the synthesis of existing peer-reviewed and technical literature, anchored by a conceptual framework figure and supplemented by tournament-scale waste projections.

The central finding is that neither of the two dominant shuttlecock material categories is environmentally defensible under rigorous scrutiny. Feather shuttlecocks carry upstream poultry

supply chain emissions that are typically excluded from informal environmental accounting, and their low durability requires replacement at a scale that, when projected across a major tournament, yields thousands of discarded units per event and potentially 75,000 to 80,000 units annually from the professional circuit alone. Synthetic shuttlecocks offer greater in-service longevity, but their resistance to degradation and composite construction render them effectively non-recyclable within current waste infrastructure. The common assumption that feathers represent the natural, sustainable option is, at best, an oversimplification unsupported by the lifecycle evidence.

An additional finding, not previously addressed in the literature, concerns the role of BWF left-wing feather selectivity regulations in concentrating and amplifying the carbon intensity of feather supply. This regulatory dimension suggests that sustainability in badminton cannot be achieved through material substitution alone; it requires engagement with the certification and procurement frameworks that govern which materials are permitted at which levels of the sport.

Promising candidate materials exist in bio-based polyamides and recycled thermoplastics, but neither has been aerodynamically validated for shuttlecock application, and this remains the most urgent research gap. Addressing it will require not just cross-disciplinary collaboration, but a willingness in the scientific community and in governing bodies to treat shuttlecock material sustainability as a legitimate and tractable engineering problem. The field can no longer afford to treat it as peripheral.

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