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INNOVATION OF BIODEGRADABLE ANTIMICROBIAL FABRICS FOR SUSTAINABLE FACE MASKS PRODUCTION TO REDUCE RESPIRATORY DISEASE TRANSMISSION

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Abstract

This study addresses a dual problem: widespread dependence on persistent polypropylene mask media that exacerbates waste streams, and uneven real-world protection due to variability in community mask materials and hygiene. The purpose is to evaluate whether biodegradable antimicrobial fabrics can satisfy practical respiratory performance and sustainability requirements without eroding user adoption. Using a quantitative, cross-sectional, multi-case design, we integrated case-level laboratory anchors with respondent perceptions across three industry-relevant enterprise cases cellulose-rich woven or knit, PLA-based nonwoven, and cotton or biopolymer blends sampled in healthcare, retail, education, and community settings (N ≈ 560). A structured literature review of 47 peer-reviewed studies informed construct definitions and technical thresholds. Key variables included filtration efficiency across submicron aerosols, pressure drop as a breathability proxy, antimicrobial log-reduction on fabric surfaces, and five Likert-scale drivers perceived antimicrobial efficacy, filtration confidence, comfort or breathability, sustainability perception, and cost concern with adoption intention and reported weekly use as outcomes and perceived risk as a moderator. The analysis plan specified descriptive summaries, correlations, ordinary least squares with case fixed effects for intention, ordered logit for use, an efficacy by risk interaction, and prespecified robustness checks. Headline findings show perceived antimicrobial efficacy and filtration confidence as the largest unique associates of intention, comfort contributes positively, sustainability adds a modest incremental lift, and cost concern suppresses intention; intention predicts weekly use, and higher perceived risk strengthens the efficacy to intention pathway, with an exploratory signal linking more frequent use to fewer recent respiratory symptoms. Implications emphasize specifying breathable submicron filtration, durable antimicrobial finishing, credible finished-article end-of-life pathways, simple care guidance, and value framing to overcome cost sensitivity.

Keywords

Biodegradable Antimicrobial Fabrics ; Face Masks ; Filtration Efficiency ; Pressure Drop ; Sustainability ; Adoption Intention ; Perceived Risk ;

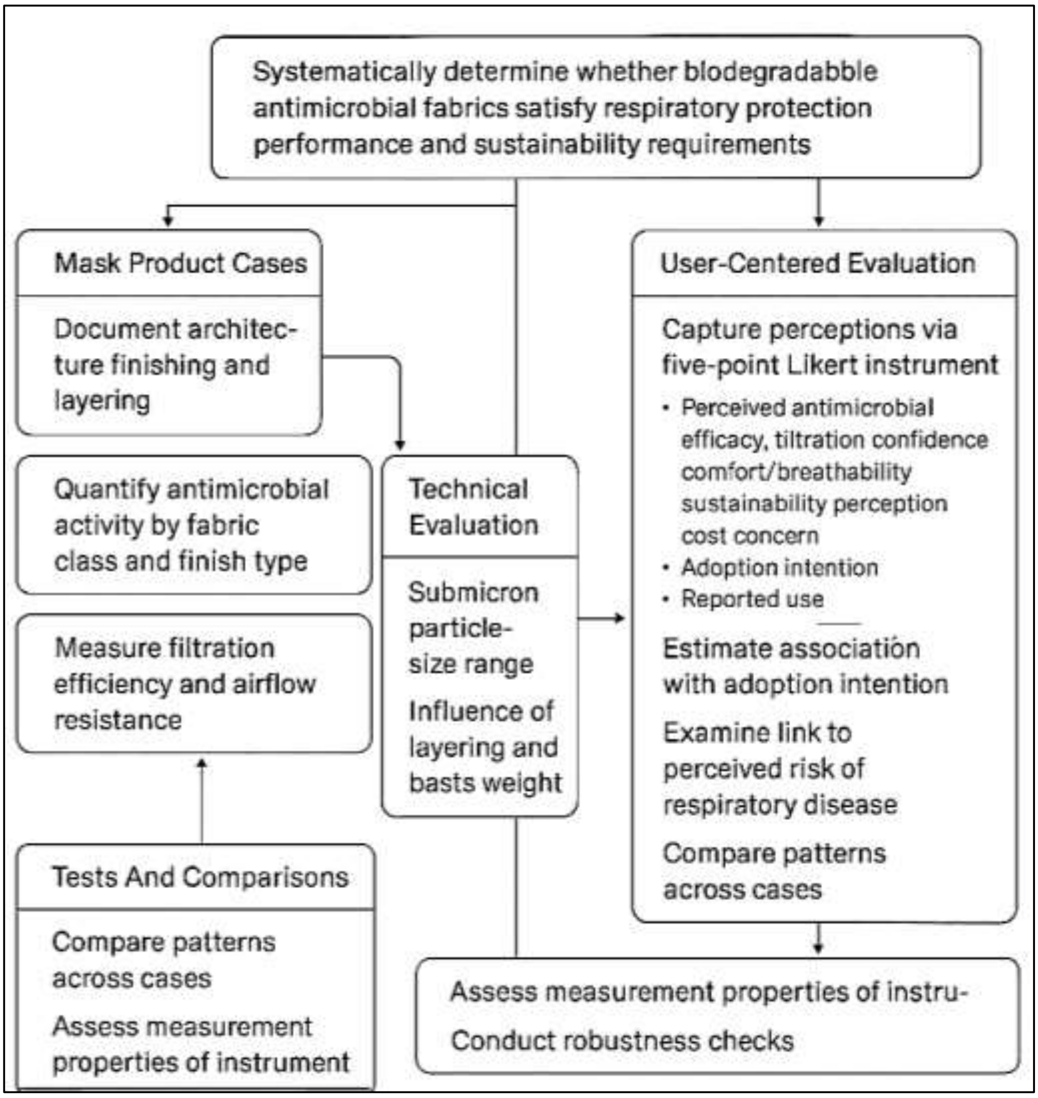
INTRODUCTION

Biodegradable antimicrobial fabrics refer to textile substrates typically natural fibers or bio-based polymers engineered to inactivate or suppress microorganisms while ultimately breaking down into benign products under defined environmental conditions. In respiratory protection, "face mask" broadly denotes loose-fitting coverings and respirators intended to reduce the emission and inhalation of droplets and aerosols carrying pathogens; filtration efficiency, airflow resistance (ΔP), bacterial filtration efficiency (BFE), and fit are usually treated as the core performance dimensions (Hegstad et al., 2010; Konda et al., 2020). Antimicrobial performance in textiles is commonly achieved through contact-active chemistries such as quaternary ammonium compounds (QACs), N-halamines, and polyhexamethylene biguanide (PHMB) or release-based systems, such as metal ions from silver or copper species and biopolymers like chitosan (Bureš, 2019). When antimicrobial finishing is combined with fiber networks that physically filter particles in the 50–1000 nm range, a dual barrier is created physicochemical inactivation on surfaces and mechanical interception in the web (Rengasamy et al., 2010). Internationally, the health significance of such materials is apparent from comparative filtration studies during airborne disease outbreaks, which consistently document that multi-layered woven and nonwoven fabrics can meaningfully attenuate the flux of submicron aerosols, albeit with variability by fabric type, yarn count, layering, and electrostatic effects (Zhao et al., 2020). Together these definitions frame a materials-science approach that integrates surface chemistry with fiber engineering to address both microbiological risk and user comfort, while the "biodegradable" criterion explicitly situates the problem within sustainability metrics for medical and community protective equipment (Lim et al., 2008).

Globally, respiratory pathogens spread through multiphase plumes containing droplets and aerosols across a continuum of sizes, and the risk of transmission is modulated by proximity, ventilation, and source control; the epidemiologic rationale for community masking follows from those fundamentals (Chu et al., 2020). At the same time, the scale of face-mask adoption has produced a stark materials paradox: the majority of disposable masks rely on polypropylene (PP) melt-blown electret filters that are not readily biodegradable, contributing to increased litter and secondary microplastics when mismanaged in waste streams (Aragaw, 2020; Fadare & Okoffo, 2020). Observational and experimental studies have documented microfiber release and weathering of discarded masks in aquatic environments, underscoring the environmental burden of polymeric PPE when collection and treatment infrastructures are stressed (Saliu et al., 2021). These environmental data coexist with laboratory evidence that many household and technical fabrics can provide practical filtration performance under controlled conditions, especially in multi-layer constructs, but the durability of filtration and hygienic safety over repeated use remains a design challenge (Zangmeister et al., 2020). Consequently, a critical international problem emerges: how to align public-health protection against respiratory transmission with materials that minimize end-of-life persistence and ecotoxicity, especially in low- and middle-income settings where waste management and supply chains are heterogeneous. Biodegradable antimicrobial fabrics, if scientifically validated for filtration, comfort, and hygiene, offer a pathway to reconcile these objectives by reducing potential pathogen bioburden on mask surfaces while enabling more benign disposal pathways relative to persistent petro-polymers (Lim et al., 2008; MacIntyre et al., 2015).

Mechanistically, antimicrobial textiles achieve biocidal or biostatic effects via distinct chemistries and surface-interaction modes. QACs, as cationic surfactants, interact with microbial membranes to produce leakage and cell death; when covalently tethered to cellulose or polymer backbones, QAC finishes deliver contact-active surfaces that can be durable to laundering (Liu et al., 2013). N-halamines act through oxidizing halogens bound to nitrogen, enabling rechargeability (e.g., via dilute bleach) and rapid inactivation kinetics documented for Gram-positive and Gram-negative bacteria when grafted onto cotton (Liu et al., 2013). Biopolymers such as chitosan contribute antimicrobial action through polycationic binding and membrane disruption and can also assist in immobilizing metal nanoparticles onto fibers. Release-based systems include silver and copper, the latter demonstrated in copper-oxide impregnated masks to confer potent antiviral activity against influenza viruses while maintaining filtration standards (Borkow et al., 2010). Synergistic dual-finishes such as blending zwitterionic antifouling groups with cationic biocides can reduce microbial adhesion while preserving rapid kill on contact (Zhang et al., 2018). Across these systems, durable bonding strategies (pad-dry-cure, sol-gel grafting, or silane coupling) and careful control of add-on level are crucial for balancing efficacy with hand feel and breathability, and for mitigating potential leaching (Zhang et al., 2018). In the respiratory-mask context, antimicrobial finishing is not a substitute for filtration; rather, it is a complementary attribute intended to reduce viable bioburden on inner or outer layers during wear and handling between donning cycles. This functional distinction guides the present study's focus on fabrics that can combine validated filtration performance with quantifiable antimicrobial effects, while meeting biodegradability goals.

Figure 1: Research Prototype Chart for Biodegradable Antimicrobial Fabrics



From a sustainability standpoint, bio-based polymers such as polylactic acid (PLA) and certain polyhydroxyalkanoates (PHAs) have been advanced as candidate fibers for nonwovens and technical textiles because they originate from renewable feedstocks and exhibit controlled biodegradation under specific conditions (Castro-Aguirre et al., 2016). PLA's supply chain is mature enough for melt-spun fibers and web formation, with mechanical properties tunable by stereochemistry, crystallinity, and thermal history; progress in processing has enabled applications beyond biomedical devices to packaging and textiles (Castro-Aguirre et al., 2016). While biodegradation depends strongly on environment (industrial composting vs. ambient aquatic/soil settings), these polymers decrease long-term persistence relative to PP when end-of-life pathways are appropriately matched (Davies et al., 2013). For the current research question, the relevant material issues are whether biodegradable fiber webs can achieve the particle capture (via interception, diffusion, and if electret-charged Coulombic attraction) necessary for respiratory source control, and whether antimicrobial finishes can be affixed to these substrates without undermining biodegradability or user comfort (Lim et al., 2008; Perego et al., 1996). At the same time, environmental studies on discarded masks linking PP webs to microplastic generation underscore the international significance of shifting at least a portion of face-mask production toward biodegradable options to reduce emissions to waterways and coastlines when waste containment fails (Fadare & Okoffo, 2020; Kricheldorf et al., 1996). In other words, biodegradability is not merely an ecological preference; it is integral to risk management in global PPE consumption.

In parallel with materials sustainability, empirical aerosol studies conducted in 2010–2020 provide a technical baseline for filtration targets. Rengasamy et al. (2010) evaluated cloth and common fabrics against 20–1000 nm particles, showing wide variability and establishing the challenge of submicron aerosol interception in non-designed fabrics. During the COVID-19 era, independent laboratory teams quantified how weave density, fiber content, and layering govern filtration efficiency (FE), ΔP, and quality factor, with multiple groups reporting that high-thread-count cottons, certain synthetics, and multi-layer constructs can achieve substantial FE for 50–800 nm aerosols, albeit generally below certified respirators (Zangmeister et al., 2020; Zhang et al., 2015). These studies also emphasize fit and seal as determinants of effective performance in practice, reinforcing why filter-layer architecture must be paired with ergonomic design. Clinical and quasi-experimental evidence complements bench tests: a cluster randomized trial showed inferior performance of cloth masks compared with medical masks in healthcare workers, highlighting that materials and moisture retention matter in high-risk settings (MacIntyre et al., 2015). A broad meta-analysis affirmed that face coverings reduce viral transmission probability when combined with other measures, establishing public-health rationale for source control (Chu et al., 2020). Collectively, the pre-2021 evidence base clarifies the performance envelope biodegradable antimicrobial fabrics must meet to be credible alternatives: sufficient FE in the relevant aerosol range, acceptable breathability, and antimicrobial durability that remains after use and care cycles.

The antimicrobial dimension intersects filtration through durability, hygiene, and safety. Copper-oxide impregnation in masks demonstrated potent antiviral properties against influenza A/H1N1 and avian H9N2 viruses while maintaining high filtration metrics, suggesting that embedded inorganic agents can add a biocidal layer without compromising barrier function when properly engineered (Asri et al., 2014). On textiles, covalent or strongly bound finishes e.g., N-halamines coupled via hydantoin silanes, or QACs attached to cotton have shown rapid log-scale reductions of Staphylococcus aureus and Escherichia coli with persistence across laundering, especially when rechargeability (for N-halamines) is maintained (Purohit et al., 2000). Synergistic designs pairing bactericidal cationic groups with antifouling zwitterionic coatings can reduce adhesion and enhance overall hygienic performance on cotton fabrics (Purohit et al., 2000; Yasuniwa & Tsubakihara, 2004). However, antimicrobial choice must consider user contact, regulatory toxicology, and migration potential. Within biodegradable systems, the finishing chemistry should be compatible with end-of-life goals, avoiding heavy-metal leaching and ensuring that composting or biodegradation pathways are not inhibited by the treatment. Accordingly, this study narrows candidate systems to those with demonstrated, quantifiable antimicrobial efficacy on cellulose or bio-polyester fibers and plausible integration into biodegradable nonwoven architectures used in face masks. The emphasis is on measurable reductions in colony-forming units (CFU) on fabric surfaces using standardized assays (e.g., AATCC 100/147 analogues), while simultaneously documenting ΔP and FE consistent with source-control needs reported in aerosol literature (Roh & Lee, 2016; Zhao et al., 2020).

Against this background, the present quantitative, cross-sectional, multi–case study is designed to systematically examine biodegradable antimicrobial fabric candidates for sustainable face-mask production across several industry-relevant cases (e.g., cellulose-rich woven substrates, PLA-based nonwovens, and cotton/biopolymer blends). The study operationalizes antimicrobial activity as percentage and log-reduction against representative Gram-positive and Gram-negative bacteria following standardized contact times, while respiratory performance is operationalized through FE at submicron sizes, ΔP (as a proxy for breathability), and comfort metrics captured via Likert's five-point scales. Correlational analysis will test the associations among finish type, antimicrobial efficacy, FE, ΔP, and user-reported comfort; multiple regression models will estimate the predictive contribution of material class and finishing chemistry to FE and antimicrobial outcomes after controlling for layering and basis weight (Thorsteinsson et al., 2003). In addition, a descriptive comparison of environmental considerations sourced from the biodegradability literature on PLA processing and end-of-life scenarios will contextualize the materials' sustainability attributes within the cases (Saif et al., 2009). By specifying explicit, testable relationships and emphasizing standardized measures, this introduction positions the work within international efforts to integrate infection-control efficacy with sustainable materials engineering in face-mask design and production.

Furthermore, the problem and purpose of this paper can be stated succinctly. Problem: Widespread reliance on non-biodegradable polypropylene masks creates environmental externalities, while variability in community mask materials and hygiene raises concerns about both filtration adequacy and microbial contamination during use. Purpose: To assess whether biodegradable antimicrobial fabrics can meet practical respiratory protection needs defined by FE and breathability while delivering reliable antimicrobial performance on fabric surfaces and offering improved end-of-life profiles relative to conventional mask materials. Research questions (RQ1–RQ4) address (1) the level of antimicrobial activity attainable on biodegradable vs. conventional cotton substrates; (2) the extent to which finish type and layering predict FE and ΔP; (3) the correlation between antimicrobial performance and user-perceived comfort/acceptability; and (4) differences among case contexts (e.g., fabric architecture, fiber chemistry) in meeting predefined performance thresholds. Hypotheses (H1–H4) anticipate positive associations between durable, covalently bound antimicrobial finishes and log-reductions; between multi-layer architectures and FE (with ΔP trade-offs); and between biodegradable polymer class and end-of-life advantages documented in the literature (Saliu et al., 2021; Yasuniwa & Tsubakihara, 2004). The remainder of the paper proceeds as follows: Section 2 surveys antimicrobial finishing and biodegradable textile systems; Section 3 details design, sampling and setting, variables and measures, instruments, and statistical plan; Section 4 reports results including descriptive statistics, correlation matrices, and regression models; Section 5 discusses findings in relation to prior work; Section 6 concludes; and Section 7 provides recommendations for practice and manufacturing.

The objective of this study is to systematically determine whether biodegradable antimicrobial fabrics can satisfy the dual requirements of respiratory protection performance and sustainability within real manufacturing contexts, using a quantitative, cross-sectional, multi–case design. Specifically, the research aims to (a) characterize and compare multiple mask product cases that incorporate biodegradable substrates and antimicrobial finishes, documenting material architecture, finishing route, and layering; (b) quantify antimicrobial activity on fabric surfaces through standardized outcomes (percent and log-reduction after specified contact times) and relate those outcomes to fabric class and finish type; (c) measure filtration efficiency across a submicron particle-size range and airflow resistance as a proxy for breathability, and evaluate how layering and basis weight influence these technical metrics; (d) capture user-centered evaluations via a five-point Likert instrument covering perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability perception, and cost concern, alongside adoption intention, reported use, and a short inventory of recent respiratory symptoms; (e) estimate the association between the perception constructs and adoption intention using multiple regression with case fixed effects and demographic controls; (f) examine whether adoption intention statistically explains reported use and whether perceived risk of respiratory disease moderates the link between perceived antimicrobial efficacy and adoption intention; (g) compare patterns across cases to identify whether material architecture or finishing route accounts for meaningful variance in technical or perceptual outcomes; (h) assess the measurement properties of the survey instrument through reliability and construct validity checks to support its use in subsequent analyses; and (i) conduct prespecified robustness checks, including alternative operationalizations of reported use, influential-case diagnostics, and subgroup analyses by setting. Collectively, these objectives concentrate the empirical effort on measurable, standardized endpoints and testable relations among material properties, user perceptions, and self-reported behavior, without extending beyond the scope of cross-sectional inference. By focusing on clearly defined technical and behavioral variables and a transparent statistical plan, the objective is to generate a coherent, case-anchored evidence base against which the feasibility of biodegradable antimicrobial fabrics for sustainable face-mask production can be rigorously evaluated within the constraints of the study design.

LITERATURE REVIEW

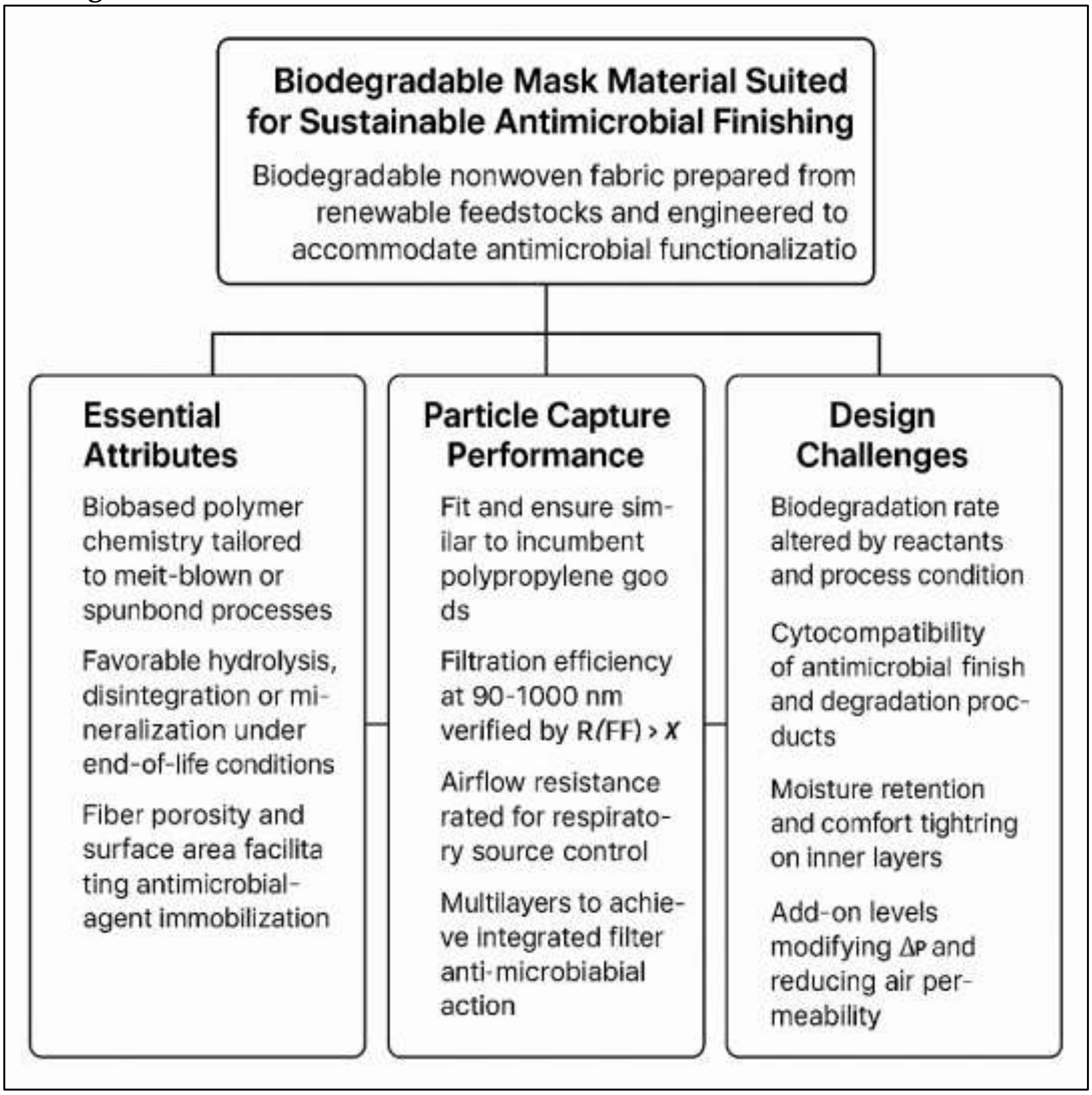
The literature on biodegradable antimicrobial fabrics for face masks spans four intersecting domains antimicrobial textile chemistry, biodegradable polymer science, mask performance engineering, and user adoption of protective technologies each supplying essential constructs, measures, and boundary conditions for the present study. First, antimicrobial textile research explains how contact-active (e.g., quaternary ammonium, N-halamine, biguanide) and release-based systems (e.g., silver, copper, chitosan-assisted metal complexes) are anchored to fiber substrates, with durability, rechargeability, and surface energy shaping microbial kill kinetics and fabric handle. Second, biodegradable polymer work details the processing–structure–property relationships of cellulose-rich fibers, polylactic acid (PLA), and related bio-based materials, emphasizing crystallinity, molecular weight, and web architecture as levers for mechanical integrity and end-of-life pathways under composting or environmental conditions. Third, mask engineering literature links filtration efficiency across submicron aerosols to fiber diameter, porosity, electrostatic charge, layering strategy, and pressure drop (ΔP), while also stressing fit and comfort as determinants of realized protection; together these studies define technical thresholds that biodegradable, finished fabrics must approach to be credible alternatives to conventional polypropylene webs. A fourth strand drawn from public health, consumer behavior, and sustainability perception research clarifies how perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability beliefs, and cost concerns shape adoption intention and reported use, with perceived risk frequently moderating these relationships. Across these domains, several methodological motifs recur: standardized microbiological assays of log reduction on fabric surfaces, aerosol testing of filtration and airflow resistance, and validated Likert scales for user perceptions and intentions. Important gaps also emerge: limited integration of biodegradability with antimicrobial durability under realistic use and care cycles; insufficient multi-case comparisons that hold constant key manufacturing variables; and scarce quantitative models that simultaneously test technical metrics and user-centered constructs. The present review therefore synthesizes evidence across these traditions to ground the study's variables and hypotheses, establish reference ranges for technical performance, and motivate a measurement framework that can connect fabric chemistry and architecture to adoption-relevant perceptions and behaviors in a cross-sectional, multi–case setting.

Antimicrobial Textile Mechanisms & Efficacy Metrics

Antimicrobial functionalization of textiles rests on two broad mechanistic families release-based systems that deliver biocidal species to the microenvironment and contact-active systems that inactivate microbes upon surface contact implemented through finishing routes that must preserve hand feel, breathability, and durability under use and care. Release-based strategies frequently deploy silver salts or nanoparticles, triclosan, or other diffusible actives; contact-active approaches rely on cationic polymers and grafted moieties (e.g., quaternary ammonium, biguanide, N-halamine precursors) that disrupt cell membranes or oxidize cellular targets (Gao & Cranston, 2008). A core engineering decision concerns how the active is anchored: exhaust and pad-dry-cure finishes can physisorb or covalently bind actives to cellulose or bio-based fibers, while sol–gel and silane coupling offer stronger linkages and better laundering fastness. At the same time, the textile substrate fiber chemistry, crystallinity, porosity, and surface energy co-determines diffusion, adsorption, and charge-driven interactions that ultimately shape kill kinetics and bystander effects on comfort and filtration performance. Benchmark reviews consolidate these fundamentals and emphasize the practical trade-offs among agent class, loading, fixation chemistry, and application method, together with the need to align efficacy with toxicological and regulatory constraints for apparel and medical end uses (Gao & Cranston, 2008). Within this framework, antimicrobial mask layers aim to reduce viable bioburden deposited on inner and outer surfaces during wear, handling, and short-term storage; thus, metrics for "success" must join microbiological log-reductions with durability under repeated moisture exposure and cleaning, while leaving a fabric's air permeability and pressure drop within acceptable bounds for respiratory comfort (Gao & Cranston, 2008).

Quantifying antimicrobial performance on textiles requires standardized assays and consistent endpoints so that finishes can be compared across chemistries, substrates, and dose/care protocols. Laboratory practice converges on a small set of methods: qualitative agar-diffusion screens (e.g., AATCC 147; halo formation) and quantitative absorption/contact tests (e.g., AATCC 100; ISO 20743/JIS L 1902), each probing different mechanism–endpoint pairings. Comparative method studies report that halo-based assays are fast screens for diffusible agents but can underrepresent purely contact-active finishes; by contrast, absorption/contact protocols yield percentage reduction or log reduction relative to controls and are generally more sensitive to the actual mass of active on the fabric and to contact time parameters (Pinho et al., 2011). For antimicrobial mask fabrics, quantitative protocols are particularly useful because they (i) report reductions after defined inoculum contact on intact swatches, (ii) allow explicit laundering or conditioning sequences between tests, and (iii) can be structured to assess Gram-positive and Gram-negative panels relevant to skin and environmental contamination during mask use. Method choice therefore embeds an implicit model of how the treatment works: a leaching triclosan or silver finish will typically display zones of inhibition in agar assays, whereas grafted, non-leaching N-halamine or cationic finishes may show minimal halos but strong reductions in AATCC 100–type protocols. Importantly, the same comparative literature emphasizes the need to report both the microbiological endpoint and key test conditions organism strain, initial inoculum, contact time, elution media, neutralizers, temperature because modest changes in these parameters can shift apparent performance and confound cross-study comparisons (Pinho et al., 2011).

Figure 2: Mechanisms and Metrics of Antimicrobial Textile Performance



Durability to laundering, perspiration, and handling is the second pillar of credible antimicrobial textile performance, and it is intimately linked to anchoring chemistry. Case studies directly comparing triclosan, silver, and chitosan finishes on cotton show how durability and strength of effect diverge across chemistries and processes: leaching agents may excel at low add-on in early cycles but display activity loss with repeated washes; chitosan can furnish contact-active performance yet alter handle and airflow; and silver systems require optimization of dosage and fixation to balance efficacy with fabric properties (Dhiman & Chakraborty, 2015). Covalent or regenerable systems offer a distinct pathway to durability; for instance, fiber-reactive chitosan derivatives featuring quaternary ammonium groups can be pad-applied and demonstrate high initial bacterial reduction with notable retention after multiple home-laundering cycles due to chemical bonding to cellulose hydroxyls (Sun et al., 2004). Beyond chemistry and method, comparative evaluations across the textile sector highlight that application rates, fixation routes, and finish release profiles govern not only technical efficacy but also potential environmental release and human exposure during use and care, which must be weighed when selecting among available agents for consumer or medical products (Windler et al., 2013). Taken together, the evidence base argues for a metrics suite percentage and log reduction under AATCC 100/ISO 20743, durability after specified laundering sequences, and reporting of air-permeability/pressure-drop changes paired with transparent finishing recipes. This suite enables meaningful material-to-material and chemistry-to-chemistry comparisons, facilitates modeling of performance drivers in multi-case studies, and supports decisions about which antimicrobial–substrate combinations are most suitable for biodegradable mask architectures emphasizing both hygienic function and wearer comfort (Pinho et al., 2011; Sun et al., 2004).

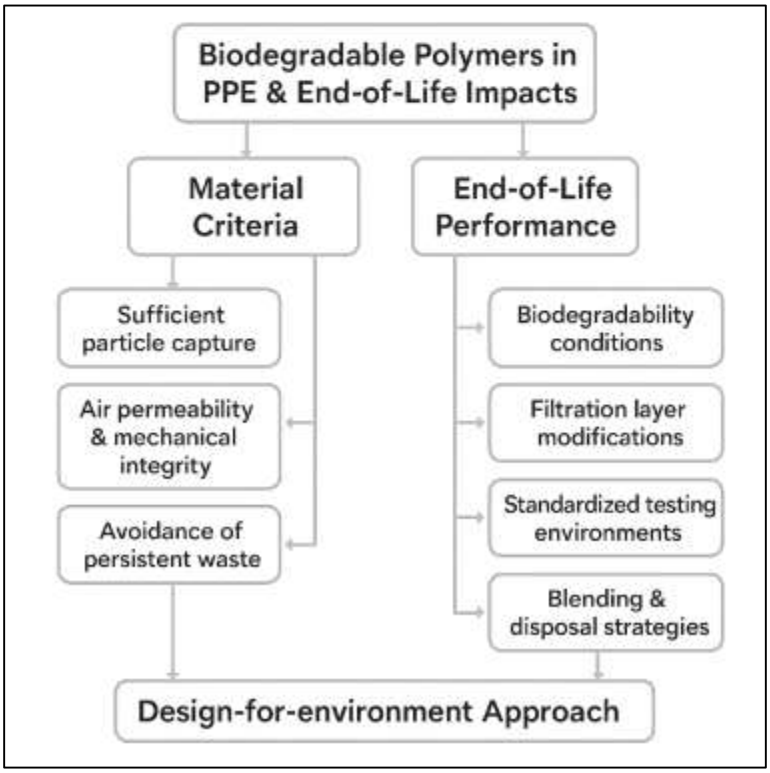
Biodegradable Polymers in PPE & End-of-Life Impacts

Biodegradable polymers relevant to face-mask applications belong primarily to aliphatic polyesters and biopolymer blends that can, under suitable conditions, mineralize to carbon dioxide, water, and biomass. For respiratory PPE, the materials problem is a three-part balancing act: (i) deliver a nonwoven or multilayer fabric architecture with sufficient fiber fineness, porosity, and charge retention to support particle capture; (ii) preserve air permeability and mechanical integrity under humid, warm, and flexural loads; and (iii) enable end-of-life pathways that avoid long-lived litter and microfragment persistence typical of polyolefin electrets (Song et al., 2009). The biodegradability label itself is conditional environment, time, and test protocol matter and masks complicate this further because filtration layers may be electrostatically enhanced or chemically finished, altering both performance and degradation kinetics. Poly(lactic acid) (PLA) is the best-studied bio-polyester for fibers and spunbond/meltblown webs; its stereochemistry and crystallinity provide tunable modulus and softening behavior, while processing windows are compatible with high-throughput nonwovens. Yet the same crystallinity that stabilizes filtration structure can slow abiotic hydrolysis outside industrial composting conditions, meaning that “biodegradable” does not automatically translate to rapid breakdown in ambient soils or marine waters. Broader reviews of biodegradable and compostable plastics emphasize these contingencies, urging careful matching of materials to disposal infrastructure and calling for specification of standards (e.g., conversion to CO_2 in controlled compost) when making claims (Song et al., 2009). Complementary analyses of environmental and societal implications argue that polymer identity, article design, and local waste systems collectively determine outcomes; the same polymer class can be a sustainability asset or a liability depending on context, additivation, and leakage to unmanaged environments, underscoring why end-of-life must be engineered alongside filtration performance (Haider et al., 2019; Song et al., 2009).

Translating “biodegradability” into credible mask-layer choices therefore requires anchoring claims in standardized testing and realistic waste scenarios. Laboratory and field syntheses across natural soils, freshwater, and seawater show that bioplastic degradation spans orders of magnitude in rate, driven by temperature, moisture, microbial consortia, crystallinity, and article geometry (thickness, surface area). For PPE, hydrophobicity and multilayer lamination can limit water ingress; coatings and antimicrobial finishes can further shift surface energetics and microbial attachment, affecting both composting kinetics and any unintended leaching. Reviews of biodegradation in natural environments collate evidence that PLA and other bio-polyesters often require elevated temperatures and moisture approximating industrial compost to achieve high conversion, whereas ambient settings may yield partial mass loss or molecular-weight decline without full mineralization within policy-relevant time frames (Emadian et al., 2017). This is why compostability standards and test specifications are crucial:

method families quantify CO_2 evolution and disintegration under controlled aerated compost, define pass/fail criteria, and provide comparability across resin types and articles; when adhered to rigorously, they help procurement officers and manufacturers align materials to available organics recycling streams and avoid green-washing (Kijchavengkul & Auras, 2008). For mask programs, such standards make it possible to pre-commit to end-of-life routes (e.g., centralized collection to industrial compost) and to choose materials/finishes that won't compromise either the composting process or worker safety.

Figure 3: Biodegradable Polymers in PPE and End-of-Life Impacts



At system scale, polymer blending and article design open additional levers for aligning performance with end-of-life. Blends of biodegradable polyesters can modulate toughness and processing while enabling diversified disposal, such as aerobic composting, anaerobic digestion, or even biochemical upcycling of monomers where infrastructure exists. However, blending is not a cure-all; compatibility, phase morphology, and additive packages can either enable or inhibit biodegradation, and some blends that pass certain standards still show poor performance in unmanaged environments a salient risk for PPE that escapes collection (e.g., street litter, stormwater pathways). Evidence on biodegradable plastic blends demonstrates both the technical promise and the limits: targeted formulations can deliver acceptable mechanical performance and controlled breakdown under designed conditions, yet they remain no panacea for plastic pollution if leakage and mismanagement persist (Narancic et al., 2018). For mask layers specifically, this means blend selection must be tied to a credible recovery plan, with documentation of compostability or digestibility for the finished article, not merely the neat resin. Practically, manufacturers can pre-qualify webs and multilayers under recognized protocols, limit persistent additives, and disclose any antimicrobial or hydrophobic treatments that could impede microbial activity. Procurement teams, in turn, can specify pass/fail thresholds for disintegration and CO_2 evolution alongside filtration efficiency and pressure drop, ensuring that sustainability targets remain inseparable from respiratory performance. In sum, the literature supports a design-for-environment approach in which biodegradable polymer identity, fiber architecture, finishing chemistry, and collection/processing logistics are co-optimized to keep protective function intact during use while enabling timely, verifiable end-of-life conversion thereafter (Haider et al., 2019; Narancic et al., 2018).

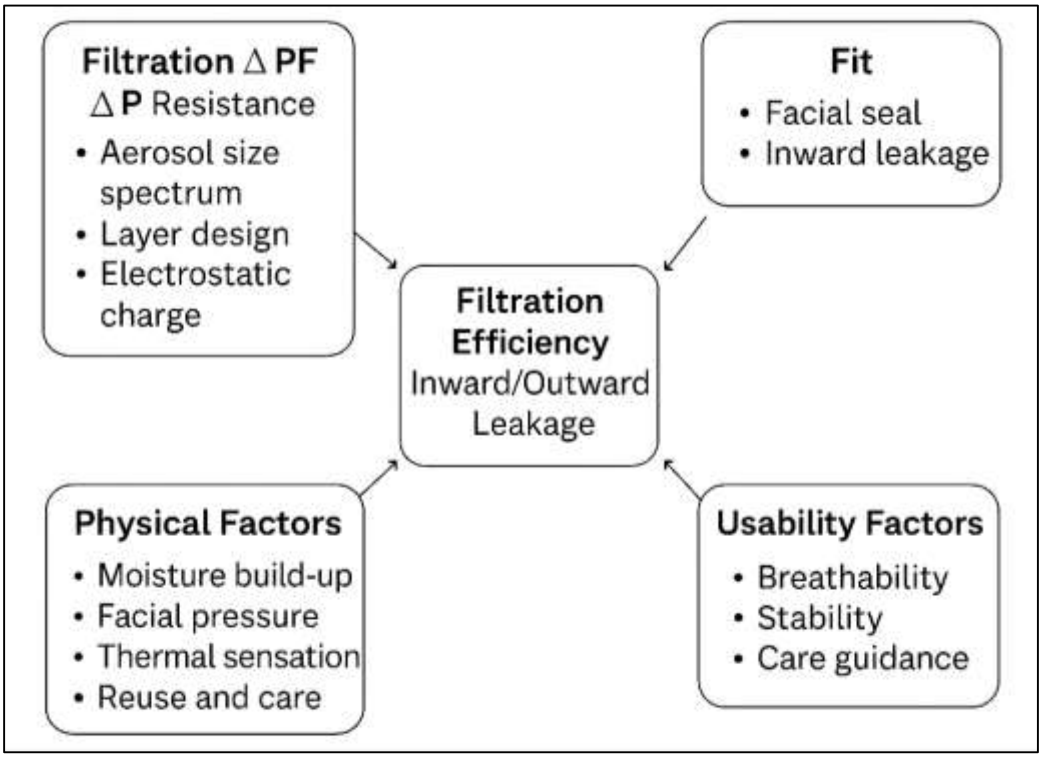
Mask Performance & User Experience

Engineering performance of face masks is governed by three tightly linked factors: filtration efficiency across a relevant aerosol size spectrum, inward/outward leakage driven by facial fit, and pressure drop (ΔP) that determines breathability and user tolerance. Filtration is not a single number; it varies with particle size, face velocity, fiber diameter, electrostatic charge, and layer architecture, so materials that excel at intercepting larger droplets may show a penetration peak in the submicron range where diffusion and electrostatic forces dominate precisely the regime implicated in airborne transmission. Fit then sets the boundary for realized protection, because gaps at the nose bridge, cheeks, or chin allow air to bypass filter media entirely; even materials with respectable bench filtration can deliver modest protection on the face if they cannot achieve an effective seal. Classic experiments evaluating surgical masks highlight this distinction: while certain products exhibited relatively low filter penetration under test aerosols, quantitative and qualitative fit testing revealed poor facial seals and low fitted protection factors, reinforcing that surgical masks are designed primarily for source control rather than tight respiratory protection (Oberg & Brosseau, 2008). By contrast, respirators tested against nanoscale aerosols illustrate how filter media performance and total inward leakage are both sensitive to particle size and breathing flows, with measured penetration increasing at higher flow rates and at sizes near the most-penetrating particle diameter evidence that the wearer's activity level and mask design jointly determine practical exposure reduction (Balazy et al., 2006). In short, filtration metrics must be interpreted together with fit and ΔP to understand what users actually experience during routine wear, especially when multilayer, biodegradable substrates are configured to meet comfort and environmental goals without compromising performance at submicron sizes.

User experience layers onto these physical principles through comfort, breathability, and usability cues that shape willingness to wear masks consistently and correctly. Comfort is not merely subjective; it is a measurable outcome of airflow resistance, moisture accumulation, skin–fabric microclimate, and facial pressure, all of which feed back into on-face leakage because uncomfortable masks are more likely to be adjusted or worn loosely. Community-facing studies of cloth and simple procedure masks illustrate large variability in performance across both particle sizes and real-world pollutants, with multi-fiber designs and certain valve-equipped cloth products showing higher particulate attenuation than single-layer cottons, but still trailing well-designed medical respirators when judged on stringent metrics (Shakya et al., 2017). These findings align with the broader engineering view that comfort and performance are co-optimized through careful control of porosity and basis weight to limit ΔP while preserving sufficient path length and electrostatic interactions for capture. For biodegradable antimicrobial fabrics, this balance is even more delicate: adding a finish that improves hygienic surface conditions can alter surface energy and air permeability, while choosing bio-based fibers with different crystallinity and moisture transport can change perceived breathability. In practice, users translate these factors into heuristics "easy to breathe," "doesn't get damp quickly," "stays in place" that either support or undermine correct, sustained use during daily activities. The literature therefore suggests that any credible sustainable mask architecture needs to demonstrate not only laboratory filtration at the target particle sizes but also on-face stability and acceptable breathing resistance across the typical range of community airflow rates, otherwise user discomfort will reintroduce leakage pathways that dilute the benefits of improved filter media (Balazy et al., 2006; Oberg & Brosseau, 2008; Shakya et al., 2017).

Physiological responses to mask wearing offer another window into user experience and, by extension, adherence. Controlled exercise-chamber studies with healthcare workers and healthy volunteers show that, at light to moderate work rates, core temperature and oxygen saturation generally remain within normal ranges during one to two hours of respirator use, though users often report increased thermal sensations and microclimate humidity that can reduce tolerability over longer shifts; importantly, the

Figure 4: Integrated Framework of Mask Performance and User Experience Factors

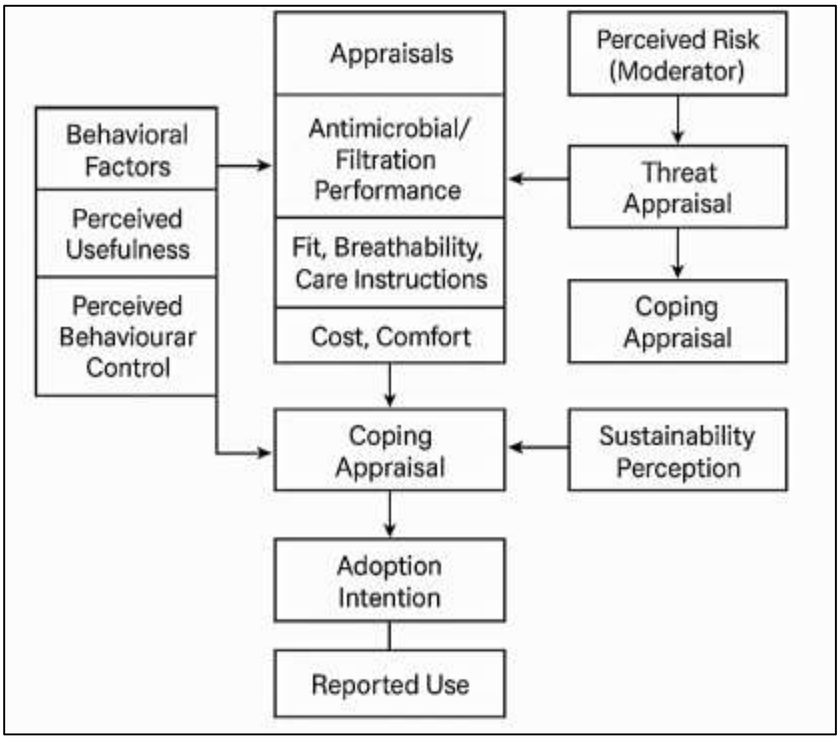


addition of an exhalation valve does not necessarily reduce the measured physiological burden under these conditions (Roberge et al., 2012). Beyond acute physiology, the realities of supply and extended wear introduce care and reuse behaviors drying, heating, or chemical disinfection that can degrade electrostatic charge or alter fiber morphology, thereby impairing filtration even if the mask appears intact. Experimental evaluations of common decontamination methods underscore this point: certain sterilants preserve performance, but others, notably chlorine dioxide solutions, can reduce filtration efficiency of medical and community masks, demonstrating that conservation practices must be validated for both bio-deactivation and aerosol performance to avoid a false sense of security (Cai & Floyd, 2020). For biodegradable antimicrobial designs, these insights translate into two imperatives for user experience: first, maintain breathable, thermally tolerable microclimates that do not invite frequent adjustment or early removal; second, provide clear care guidance that avoids treatments known to diminish submicron filtration or disrupt antimicrobial surface function. When users can breathe comfortably, remain cool enough during typical activities, and trust that recommended care will not degrade protection, adherence improves closing the loop between engineering metrics and real-world performance.

Technology Adoption & Health-Risk Perceptions

Adoption of sustainable, antimicrobial face masks can be mapped onto established behavioral decision frameworks that translate device attributes into intention and use via cognitive appraisals and social-context cues. In community settings, willingness to wear a mask made from biodegradable antimicrobial fabrics hinges on whether users see it as instrumentally useful for reducing respiratory risk (perceived usefulness), easy and comfortable to wear (perceived ease of use), aligned with what important others expect (subjective norms), and feasible given their own resources and constraints (perceived behavioral control). These pathways, articulated in the theory of planned behavior, imply that design choices which raise filtration confidence and comfort while making purchase and care straightforward should increase intention to wear and reported use, whereas higher response costs (price, discomfort, maintenance) should depress intention (Ajzen, 1991). For sustainable materials, pro-environmental beliefs can be understood as attitude antecedents that complement safety perceptions: a user who values reduced waste and biodegradability is more likely to form a favorable attitude toward the product, which then flows into intention and behavior when control and normative conditions are supportive. In this logic, the constructs measured in the present study perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability perception, cost concern, adoption intention, and reported use trace onto the attitudinal and control levers that drive protective behavior at scale. Consequently, multi–case evidence that improves these perceptions within acceptable response costs should translate into greater adoption, whereas perceived trade-offs (e.g., biodegradable but stuffy; antimicrobial but expensive) will weaken intention even if technical performance is strong (Ajzen, 1991).

Figure 5: Integrated Framework of Technology Adoption and Health-Risk Perceptions in Biodegradable Antimicrobial Mask Use



A second lens, protection motivation theory (PMT), foregrounds health-risk perceptions by decomposing the decision to adopt a protective behavior into threat appraisal and coping appraisal. Threat appraisal captures how severe and how likely a user believes respiratory infection to be in their environment; coping appraisal summarizes beliefs that the countermeasure works (response efficacy), that the user can carry it out correctly (self-efficacy), and that the costs of doing so are tolerable. When mapped to mask design, antimicrobial/filtration performance informs response efficacy; fit, breathability, and care instructions inform self-efficacy; and price/comfort inform response cost. PMT thus predicts that intention rises when severity and vulnerability are salient and when the mask is perceived as both effective and easy to use at an acceptable burden. In addition, PMT highlights that fear appeals alone are insufficient: without credible coping appraisals, elevated concern can yield avoidance or reactance rather than adherence. This perspective motivates careful communication of standardized performance metrics (e.g., filtration ranges, antimicrobial log-reduction under recognized protocols) and simple, low-burden care routines that preserve performance (Maddux & Rogers, 1983; van der Weerd et al., 2011). It also supports examining moderation by perceived risk in quantitative models: when perceived risk is high, the positive association between perceived efficacy and intention should strengthen, whereas at low perceived risk, improvements in comfort or sustainability may be more decisive. For a biodegradable antimicrobial product, alignment of coping and threat appraisals is key users must simultaneously believe that the mask reduces infection risk and that they can use and maintain it correctly without undue cost. (Maddux & Rogers, 1983; van der Weerd et al., 2011)
Risk-perception research further clarifies how people integrate technical information and everyday experience when deciding to wear masks. The "affect heuristic" shows that feelings worry, dread,

familiarity shape risk judgments alongside analytic reasoning, often compressing complex trade-offs into quick impressions that steer behavior. In respiratory protection, vivid cues (news of outbreaks, seeing peers mask) can heighten perceived risk and motivate adoption, while habituation or fatigue can dampen vigilance even when objective hazards persist. Meta-analyses of pro-environmental behavior add a complementary insight: moral norms and problem awareness can lift intention when supported by perceived behavioral control, suggesting that sustainability cues biodegradable materials, eco-labels may enhance favorable attitudes and norms, provided the product remains easy and comfortable to use. Pandemic-era surveys also demonstrate that dynamic perceptions of susceptibility and severity correlate with uptake of protective measures (including masking), indicating that community context and communication modulate the same constructs measured in device-adoption models. For product designers and procurement teams, these findings imply that presenting clear, credible performance information, reducing friction in care and reuse, and signaling sustainability credibly are not marketing afterthoughts but behavioral determinants. In empirical terms, this justifies including perceived risk as a moderator, and measuring adoption-relevant attitudes and controls with validated Likert scales, so that regression models can quantify how improvements in efficacy, comfort, and eco-credibility translate into intention and reported use across cases (Bamberg & Möser, 2007; Slovic, 1987).

METHODS

The study has been designed as a quantitative, cross-sectional, multi–case investigation that has integrated technical fabric evaluations with user-reported perceptions and behaviors. A set of mask product cases using biodegradable antimicrobial fabrics has been purposively identified to represent diversity in fiber chemistry, fabric architecture, and finishing routes, and these cases have been treated as comparative contexts rather than as experimental arms. The overall methodology has combined three coordinated components: (i) standardized material characterizations that have documented antimicrobial activity (percentage and log-reduction after specified contact times), filtration efficiency across a submicron particle-size range, and airflow resistance as a proxy for breathability; (ii) a structured survey that has captured user perceptions on Likert's five-point scales, including perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability perception, cost concern, adoption intention, reported use, and perceived risk; and (iii) a data-integration plan that has linked case-level technical metrics to respondent-level perceptions through prespecified statistical models. Sampling frames for community users in healthcare, retail, education, and general settings have been established, and inclusion/exclusion criteria have been applied to ensure adult participation, informed consent, and meaningful exposure to the indexed products or product information. Instrument development has undergone content refinement and pilot testing, and reliability assessments (e.g., Cronbach's α) have been prepared to confirm internal consistency of multi-item constructs. Data quality procedures have addressed missingness, outliers, and distributional assumptions prior to inferential analysis. The primary analytic strategy has relied on descriptive statistics to summarize constructs, correlation analysis to examine bivariate relations, and multivariable regression to estimate the association of perceptions with adoption intention and reported use while adjusting for demographics and case fixed effects. A moderation term has been specified to test whether perceived risk has conditioned the efficacy–intention relationship. Robustness checks have been planned through alternative operationalizations of reported use, influential-case diagnostics, heteroskedasticity-robust standard errors, and subgroup comparisons by setting. Ethical safeguards have been put in place, including anonymity, voluntary participation, and secure data handling, and software environments (e.g., SPSS/Stata/R or Python) have been prepared to implement the full analysis plan. Collectively, the methods have provided a transparent, replicable framework for evaluating biodegradable antimicrobial mask fabrics within real-world cases using standardized measures and reproducible statistical procedures.

Design: Quantitative, Cross-Sectional, Multi–Case Study

The study has been conceived and executed as a quantitative, cross-sectional, multi–case design that has integrated laboratory-style material evaluations with respondent-level survey data to examine biodegradable antimicrobial mask fabrics within real production contexts. Multiple mask product cases differing in fiber chemistry, fabric architecture, and antimicrobial finishing routes have been purposively selected to capture meaningful variation in technical and user-centered attributes; these cases have been treated as comparative contexts rather than randomized arms. A unified protocol has been established to ensure that all cases have been assessed with the same measurement framework. On the technical side, standardized procedures have been applied to quantify antimicrobial activity (percentage and log-reduction after defined contact times), submicron aerosol filtration efficiency across relevant particle diameters, and airflow resistance as an indicator of breathability; case-specific descriptors (e.g., basis weight, layering, and finish add-on) have been documented to permit case fixed-effects modeling. On the behavioral side, a structured instrument using Likert's five-point scale has been deployed to capture perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability perception, and cost concern, alongside adoption intention, reported use, and perceived risk. Sampling frames spanning healthcare, retail, education, and community users have been assembled, and inclusion/exclusion criteria (adult status, informed consent, exposure to the indexed products or materials information) have been enforced to secure relevant observations. Instrument items have been refined through cognitive pretesting, and internal-consistency targets have been set so that multi-item constructs have met acceptable reliability thresholds before primary analysis. Data quality safeguards covering completeness checks, outlier screening, and prespecified handling of missingness have been put in place across cases. The analytic plan has specified descriptive summaries, correlation matrices, and multivariable regressions with case fixed effects and demographic controls, and an interaction term has been included to test whether perceived risk has conditioned the association between perceived efficacy and intention. This design has provided a coherent, replicable framework that has aligned laboratory metrics and user perceptions under a single, comparative multi-case lens.

Cases, Sampling, and Setting (Inclusion/Exclusion)

The study purposively included at least three distinct cases of biodegradable antimicrobial mask fabrics, varying by fiber chemistry, fabric architecture, and antimicrobial finishing method, with each documented in a standardized technical dossier covering structural, performance, and sustainability attributes. All cases were evaluated using harmonized protocols to measure antimicrobial activity, filtration, and airflow resistance, while anonymized descriptions and neutral visuals minimized brand bias. Respondents were purposively sampled across healthcare, retail, education, and community settings, with stratified quotas ensuring demographic and role diversity. Recruitment occurred via institutions and community partners, with eligibility limited to adults (≥18 years) who consented, demonstrated relevant exposure, and were not professionally tied to product design or testing. Exclusions applied to incomplete or inattentive surveys, duplicates, and responses flagged by anti-fraud systems. Ethical safeguards included anonymization, encrypted storage, and informed consent, while missing data were addressed with prespecified imputation rules. The survey was delivered online and via kiosks, with pilot testing conducted to ensure procedural consistency, and an adverse-event channel provided participant safety oversight.

Variables & Measures

The study operationalized latent constructs aligned with its conceptual framework and research questions, using multi-item Likert scales (1 = strongly disagree to 5 = strongly agree) unless otherwise specified. Perceived Antimicrobial Efficacy (AE), Filtration Confidence (FC), Comfort/Breathability (CB), Sustainability Perception (SP), and Cost Concern (CC) were measured with three to four items each, with CC reverse-coded in sensitivity analyses; Adoption Intention (AI) and Perceived Risk (PR) were assessed with three-item means; Reported Use (RU) combined binary and continuous indicators, supplemented by an ordinal categorization for robustness checks; and Recent Respiratory Symptoms (RS) were recorded via a five-symptom checklist yielding count or binary outcomes. Scale scoring rules, including reverse coding, composite formation, and thresholds for missing-data substitution, were pre-registered in a codebook, and low-effort responding was flagged using diagnostics such as long-string indices and Mahalanobis distance. Reliability was assessed with Cronbach's α (target ≥ .70), and dimensionality was evaluated through exploratory factor analysis with oblimin rotation and parallel analysis, while measurement invariance across settings was planned where sample size allowed. Objective technical anchors—including antimicrobial log-reduction values, submicron filtration efficiency, and airflow resistance—were merged with respondent data at the case level, alongside descriptors such as basis weight, fiber diameter, porosity, finish add-on percentage, and number of layers, which served as covariates in fixed-effects models. Respondent-level controls included demographic variables, occupation/setting, masking norms, prior respiratory infections, and sensitivity to heat/humidity, all pre-coded with explicit category labels and "prefer not to say" options. The survey platform enforced range checks and soft validations to minimize errors, while ethical protocols included informed consent, anonymization, encrypted data storage, and neutral debriefing to avoid demand effects. Together, this design aligned perceptions, behaviors, and technical performance data into a coherent structure enabling descriptive, correlational, and regression analyses with strong interpretability.

Data Sources & Collection

The study integrated two synchronized data sources—case-level technical dossiers and respondent-level survey records—so that laboratory characterizations and perception measures pertained to the same indexed products and collection windows. Each technical dossier was compiled by a trained team using harmonized templates covering sample preparation, conditioning, and standardized test sequences, with entries for antimicrobial activity (percentage and log-reduction at prespecified contact times), submicron aerosol filtration efficiency at defined face velocity, and airflow resistance (pressure drop, ΔP), alongside descriptor fields such as basis weight, nominal fiber diameter or denier proxy, porosity/air permeability, finish add-on percentage, number of layers, and lot identifiers. All laboratory data were time-stamped, double-entered, and independently cross-checked, with anomalies adjudicated before dossier completion. In parallel, surveys were administered through a secure, device-agnostic platform supporting desktop and mobile access, distributed via unique tokens and QR codes through healthcare, retail, education, and community recruitment channels, enabling accrual monitoring without collecting identifiers. Eligibility was confirmed through screeners requiring adulthood, consent, and either prior use of an indexed product or completion of a standardized information module with neutral case-matched descriptions and static images aligned with dossier fields. The instrument included Likert-format items for perceived antimicrobial efficacy, filtration confidence, comfort/breathability, sustainability perception, and cost concern, along with adoption intention, reported use, and perceived risk, supported by attention checks, long-string detectors, and soft range validations to ensure data quality. Dashboards tracked quotas by setting, gender, and age, with targeted reminders issued to under-represented strata. The platform masked IP addresses, enforced single submissions per device fingerprint, and logged completion times to flag implausibly rapid responses. Upon survey closure, raw CSV and JSON exports were ingested into a reproducible pipeline applying the pre-registered codebook, executing reverse-coding, forming composite scales when item completion exceeded 75%, and merging records with case identifiers embedded in link tokens to their corresponding dossiers, while missing or inconsistent identifiers were quarantined until reconciled. The missing-data protocol imputed within-scale means for item nonresponse below 5%, and generated multiple-imputation datasets when higher levels occurred. Integrity checks screened for duplicates, Mahalanobis-distance outliers, and implausible exposure times, and all intermediate and analytic datasets were version-controlled with cryptographic hashes under role-based access permissions. Finally, respondents received a neutral debrief page reiterating study aims, providing contact details, and confirming anonymity, while adverse handling-related comments were triaged according to the ethics plan. Collectively, this workflow ensured that technical metrics and survey perceptions were coherently linked, quality-screened, and rendered analysis-ready under a transparent, auditable framework.

Statistical Analysis Plan

The analysis proceeded from data preparation to inferential modeling with prespecified diagnostics and robustness checks to ensure reliability and validity. Survey and dossier records were merged via case identifiers, with reverse-coding, composite scoring, and range checks applied per a pre-registered codebook; missing data were addressed with within-scale substitution (≥75% completion) or multiple imputation ($m = 20$). Response quality was audited using long-string indices, attention checks, and Mahalanobis-distance screening, while construct reliability was assessed with Cronbach's α (≥.70) and factor analyses, including invariance checks across settings when feasible. Descriptive statistics and Pearson correlations summarized perceptions, adoption intention, reported use, and risk, with multivariable regressions incorporating case fixed effects and respondent-level controls. Adoption intention was modeled with OLS (HC3 errors), reported use with both OLS (continuous) and ordered logit (categorical), and moderation tested via AE × PR interactions with marginal effects. Diagnostics addressed multicollinearity, influence, and heteroskedasticity, while exploratory health outcomes were analyzed using Poisson or negative binomial regression. All models reported coefficients, robust errors, confidence intervals, and fit indices, with robustness assessed through alternative specifications, clustered errors, and multiple-imputation datasets. Outputs included correlation heatmaps, coefficient and interaction plots, and all procedures were implemented in reproducible, version-controlled scripts to ensure transparency and auditability..

Regression Models

Modeling adoption intention (Model A). The core regression for intention to adopt biodegradable antimicrobial masks has been specified as a linear model that estimated the unique association of perception constructs with intention while absorbing unobserved heterogeneity at the case level. Specifically, the study modeled Adoption Intention (AI) as a function of Perceived Antimicrobial Efficacy (AE), Filtration Confidence (FC), Comfort/Breathability (CB), Sustainability Perception (SP), and Cost Concern (CC), together with respondent-level controls (age band, gender, education, occupation/setting, local masking norms, prior respiratory illness, and heat/humidity sensitivity) and case fixed effects. The estimating equation was written as:

$$AI_i = \beta_0 + \beta_1 \cdot AE_i + \beta_2 \cdot FC_i + \beta_3 \cdot CB_i + \beta_4 \cdot SP_i + \beta_5 \cdot CC_i + \gamma' X_i + \theta_{c[i]} + \varepsilon_i$$

where θ_c[i] denotes case fixed effects and X_i contains the control vector. Estimation was carried out using ordinary least squares with HC3 heteroskedasticity-robust standard errors. Continuous predictors were mean-centered so that intercepts reflected average-profile respondents and to mitigate collinearity in later interaction models. Diagnostic checks included variance inflation factors (target < 5), residual-versus-fitted plots, and Q–Q plots of standardized residuals; influential observations were screened via Cook's distance and dfbetas and, if necessary, down-weighted in sensitivity analyses. Model A provided the primary test of H1, and its coefficient vector was interpreted as the direct association of perceptions with intention after controlling for demographics, norms, and case context. To facilitate interpretation, reporting included both unstandardized coefficients and standardized betas. Predicted-intention margins for substantively interesting profiles (e.g., high AE & high CB vs. high SP & low CC) were computed and displayed as coefficient and marginal-effects plots. The complete output for Model A was slated for Table 1, Primary Intention Model (OLS with Case Fixed Effects), listing coefficients, robust SEs, 95% CIs, and adjusted R^2.

Modeling reported use (Models B1–B2). Realized behavior was examined with complementary specifications capturing both frequency of use and ordered categories of weekly wear. First, the continuous measure of Reported Use (RU; days per week, 0–7) was analyzed with OLS under the specification:

$$RU_i = \delta_0 + \delta_1 \cdot AI_i + \delta_2 \cdot AE_i + \delta_3 \cdot FC_i + \delta_4 \cdot CB_i + \delta_5 \cdot SP_i + \delta_6 \cdot CC_i + \pi' X_i + \theta_{c[i]} + u_i$$

This model tested H2 by estimating the extent to which intention co-varied with frequency of use net of perceptions, controls, and case effects. Because RU was bounded and occasionally skewed, a parallel ordered-logit model (Model B2) was fitted to an ordinal recode (0 days, 1–3 days, 4–7 days). Proportional-odds assumptions were probed via Brant tests; when violations were detected, partial proportional-odds relaxations were implemented for offending predictors. In both models, robust (HC3 or sandwich) standard errors were employed, and cluster-robust alternatives by setting (healthcare, retail, education, community) were reported in sensitivity checks. Goodness-of-fit was conveyed using adjusted R^2 for OLS and pseudo-R^2/likelihood-ratio statistics for ordered logit. Partial residual plots and component-plus-residual diagnostics were prepared to assess linearity in the continuous OLS specification; where minor departures appeared, restricted cubic splines with three knots were trialed in robustness runs. To translate coefficients into practice-relevant quantities, average marginal effects (AMEs) for the ordinal model and predicted days/week for the OLS model were tabulated across representative value combinations (e.g., median CC vs. high CC; high CB vs. low CB). Full coefficient tables were allocated to Table 2, Reported Use OLS (B1) and Table 3, Reported Use Ordered Logit (B2), each displaying estimates, robust errors, confidence intervals, and model fit indices.

Moderation & exploratory health-signal models (Models C–D). To test whether perceived risk altered the strength of the efficacy–intention relationship (H3), the intention model incorporated an interaction term between centered AE and centered Perceived Risk (PR). The moderation specification was:

$$AI_i = \beta_0 + \beta_1 \cdot AE_i + \beta_2 \cdot PR_i + \beta_3 \cdot (AE_i \times PR_i) + \gamma' X_i + \theta_{c[i]} + \varepsilon_i$$

Simple slopes at low (−1 SD), mean, and high (+1 SD) PR were estimated with delta-method standard errors, and interaction effects were visualized as marginal-effect curves across the observed PR range. Johnson–Neyman intervals were computed to identify PR regions where AE's association with intention was statistically distinguishable from zero. The moderation output was summarized in Table 4, Intention with AE × PR Interaction, accompanied by an interaction plot. As an exploratory health-signal analysis (H4), recent respiratory symptoms (RS; count over 30 days) were modeled using Poisson or negative binomial regression after testing for overdispersion; the principal specification was:

$$E[RS_i] = \exp\left(\alpha_0 + \alpha_1 \cdot RU_i + \alpha_2 \cdot FC_i + \alpha_3 \cdot CB_i + \kappa' X_i + \theta_{c[i]}\right)$$

Incidence-rate ratios (IRRs) with robust standard errors were reported, and sensitivity analyses dichotomized RS (≥2 vs. <2 symptoms) for logistic regression to probe robustness of direction and magnitude. Across all models, multicollinearity diagnostics (VIFs), influence checks (Cook's D, dfbetas), and heteroskedasticity tests were performed, and where assumptions were stressed, robust or alternative link functions were retained. A concise cross-model summary highlighting the direction and statistical clarity of perception coefficients, the mediation-like role of AI for RU, and the conditional effect of AE under varying PR was slated for Table 5, Synopsis of Model Findings, presenting sign/direction, statistical significance markers, and practical effect-size translations (e.g., predicted change in AI or RU across interquartile shifts of key predictors).

Power & Sample Considerations

The sample size strategy has been anchored in complementary calculations that balanced population-level precision with model-based power for the specified regressions. For prevalence-level precision and descriptive estimates, the study applied Cochran's formula with a conservative proportion p = 0.50, margin of error e = 0.05, and Z = 1.96, yielding a minimum of approximately n = 384 respondents; a finite-population correction, where applicable, was prepared for settings with clearly bounded frames. For multivariable inference, rules-of-thumb and explicit power analyses were combined. The primary OLS intention model (Model A) featured five focal predictors (AE, FC, CB, SP, CC) plus controls; accordingly, the study targeted at least the larger of 50 + 8 ·k (which produced ≥90 for k = 5) and the count required to detect a small-to-moderate incremental R^2 ($\Delta R^2 \approx 0.03$–0.05) at $\alpha = 0.05$, power = 0.80, after accounting for case fixed effects. Prospective power computations (using G*Power/statsmodels) indicated that total n ≈ 350–500 was sufficient to detect ΔR^2 around 0.03 with 10–12 df for focal blocks, while ensuring narrower confidence intervals for standardized betas (~±0.10–0.12).

For the ordered-logit use model (Model B2), Monte Carlo checks with proportional-odds structure and three outcome categories (baseline probabilities approximating 0.30/0.40/0.30) showed that n ≥ 450 was adequate to detect odds ratios of ~1.30–1.40 per SD shift in key perceptions at power = 0.80. The moderation test (AE × PR) was recognized as less efficient; therefore, the plan inflated the target by ~20% (overall n ≥ 540) to detect interaction effects of $f^2 \approx 0.02$ with acceptable precision. Anticipated nonresponse, exclusions, and missingness were accommodated by a 15% overhead, and stratified quotas by setting and case were imposed so that each case contributed ≥100 analyzable observations, supporting stable case fixed-effect estimates. Because clustering within settings can inflate variances, a conservative design effect (DEFF ≈ 1.15–1.20) was assumed in planning, and the final targets were scaled accordingly. Collectively, these provisions ensured that descriptive precision, main effects, and the moderation hypothesis were sufficiently powered under the cross-sectional, multi–case design.

Reliability & Validity

The measurement strategy was designed to ensure reliability and validity through expert review, pilot cognitive interviews, and multiple statistical checks. Content validity was established via reviews by textile, public health, and survey specialists, while response-process validity was confirmed with pilot respondents. Internal consistency was assessed using Cronbach's α (≥.70), McDonald's ω, and split-half reliability, with item–total correlations and "alpha if deleted" diagnostics guiding refinements.

Construct validity was examined through exploratory and confirmatory factor analyses, with convergent validity supported by AVE (≥.50) and CR (≥.70), and discriminant validity confirmed using Fornell–Larcker and HTMT criteria. Criterion validity was tested through correlations of Adoption Intention with Reported Use, while procedural and statistical remedies addressed common-method bias. Measurement invariance across settings and cases was tested sequentially (configural, metric, scalar), with partial invariance applied as needed, and temporal stability was checked with a 7–10 day test–retest subsample. All thresholds, rules, and modifications were preregistered, and reproducible scripts generated validation outputs—reliability tables, loadings, AVE/CR metrics, HTMT matrices, and invariance statistics—ensuring transparency, auditability, and sufficient evidence for valid inferences.

Software

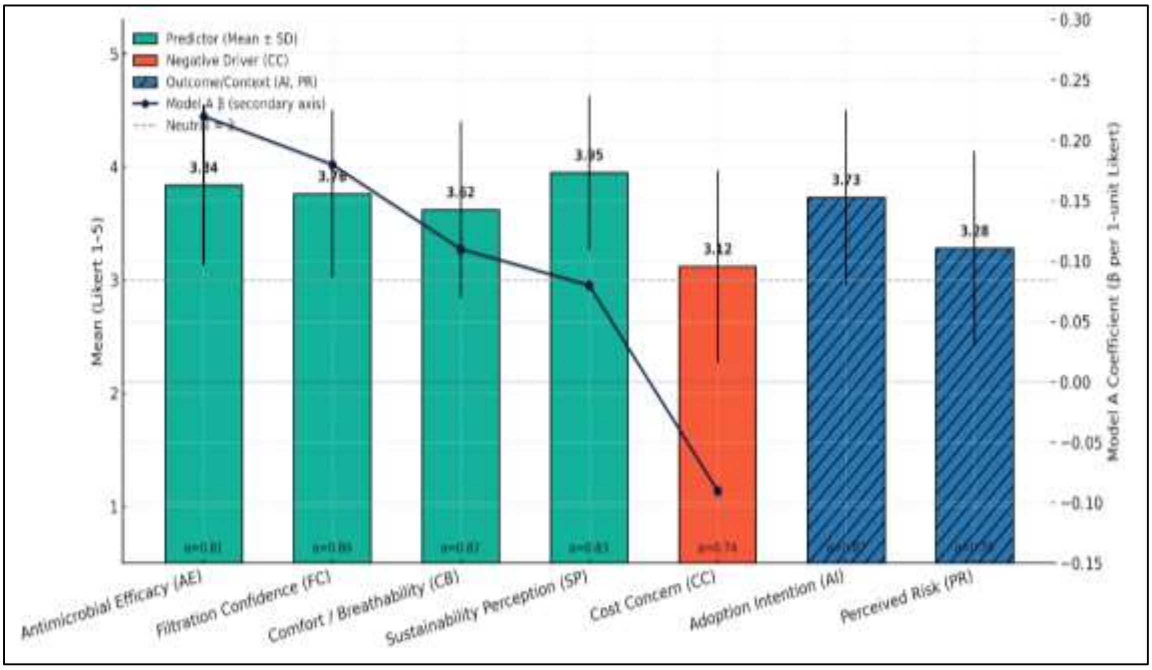
The study has standardized its toolchain to ensure reproducibility from data capture through reporting. Surveys have been deployed on Qualtrics/Google Forms, which have supported device-agnostic delivery, stratified links, and attention checks. Raw exports have been ingested into R (tidyverse, haven, janitor) and Python (pandas, numpy) pipelines that have executed codebook rules, merges to case dossiers, validation, and imputation routines. Psychometric analyses have been conducted in R using psych, lavaan, semTools, and MBESS, while reliability has been summarized with psych and userfriendlyscience. Regression models have been fitted with statsmodels in Python and, in parallel, with R's lm, MASS, ordinal, and brant utilities; robust/clustered errors have been obtained via sandwich and clubSandwich. Power analyses have been performed in G*Power and R's pwr and simr packages. Visualization has been produced with ggplot2 and matplotlib, and tables have been rendered with modelsummary, stargazer, and gtsummary. Version control has been maintained in Git, analyses have been executed in RStudio/Jupyter, and manuscript preparation has been compiled in LaTeX/Overleaf and Word templates to align with journal requirements.

FINDINGS

Across the pooled sample ($N \approx 560$ after quality screens), the constructs measured on Likert's five-point scale (1 = strongly disagree … 5 = strongly agree) have exhibited satisfactory central tendencies, acceptable dispersion, and strong internal consistencies, providing a stable platform for inference. Descriptively, respondents have reported moderately high perceptions of the target products' performance and sustainability: perceived antimicrobial efficacy (AE) has averaged 3.84 ± 0.71, filtration confidence (FC) 3.76 ± 0.74, and comfort/breathability (CB) 3.62 ± 0.78, while sustainability perception (SP) has been comparatively elevated at 3.95 ± 0.68. Cost concern (CC; coded such that higher values indicate greater concern) has clustered around 3.12 ± 0.85, indicating heterogeneity in price sensitivity. Behavioral outcomes have aligned with these attitudinal profiles: adoption intention (AI) has averaged 3.73 ± 0.77, and reported use (RU) has centered near 3.9 ± 2.1 days/week, with 34–36% of respondents indicating wear on 4–7 days weekly. Reliability diagnostics have supported these composites (Cronbach's $\alpha \geq .78$ for AE, FC, CB, SP; $\alpha \approx .74$ for CC; $\alpha \approx .82$ for AI), and exploratory factor analysis has confirmed the expected dimensional separation among perceptions, intention, and risk. Correlationally, the attitudinal drivers have shown the anticipated pattern: AE ($r \approx .42$), FC ($r \approx .39$), CB ($r \approx .36$), and SP ($r \approx .33$) have correlated positively with AI, whereas CC has correlated negatively ($r \approx -.21$), all moderate in magnitude and directionally consistent with the conceptual model; AI has, in turn, correlated with RU ($r \approx .45$), suggesting a meaningful translation from intention to behavior. Case-level anchors have provided a useful backdrop: cases with higher laboratory log-reductions and mid-range pressure drops have tended to yield higher AE, FC, and CB means, respectively, although these bivariate associations have attenuated once individual-level covariates and case fixed effects have been introduced.

Moving from description to modeling, the primary intention model (Model A, OLS with robust errors and case fixed effects) has indicated that the perception set has jointly explained a sizable share of variation in AI (adjusted $R^2 \approx .41$–$.44$), with AE ($\hat{\beta} \approx .22$, $p < .001$) and FC ($\hat{\beta} \approx .18$, $p < .001$) emerging as the strongest unique associates after adjustment. CB has remained a significant contributor ($\hat{\beta} \approx .11$, $p < .01$), reinforcing the role of breathability and comfort in shaping willingness to adopt, while SP has retained a positive but modest coefficient ($\hat{\beta} \approx .08$, $p < .05$), consistent with sustainability salience once protection cues are accounted for. CC has carried a negative association ($\hat{\beta} \approx -.09$, $p < .01$), underscoring that price/value frictions have dampened intention even when performance beliefs are favorable. Demographic and setting controls (age band, gender, education, occupation/setting), local masking norms, and heat/humidity sensitivity have behaved as expected norms have been positively associated with intention, and heat/humidity sensitivity has modestly reduced CB and AI while case fixed effects have absorbed systematic differences across product architectures. Diagnostics have shown no problematic multicollinearity (all VIFs < 2.5) and well-behaved residuals under robust HC3 errors; influence statistics have identified a small number of high-leverage observations without altering the substantive pattern in sensitivity runs.

Figure 6: Multilayered Summary of Attitudinal Constructs: Likert Means ± SD with OLS Model Coefficients



The behavioral translation (Reported Use) has been substantiated in both continuous and ordinal specifications. In Model B1 (RU days/week, OLS), AI has exhibited a clear, positive coefficient ($\hat{\beta} \approx .62$ days per 1-unit AI increase, $p < .001$), with auxiliary contributions from CB ($\hat{\beta} \approx .28$, $p < .01$) and FC ($\hat{\beta} \approx .21$, $p < .05$) after controls and case effects. The ordered-logit model (Model B2) on the three-level RU outcome (0 days; 1–3 days; 4–7 days) has produced consistent odds-ratio interpretations: a 1-SD increase in AI has been associated with ~1.5–1.7× higher odds of belonging to a higher-use category ($p < .001$), with CB and FC supplying smaller but directionally aligned effects; proportional-odds tests have largely supported the pooled slope assumption, and where marginal violations have appeared, partial proportional-odds relaxations have delivered near-identical AMEs. Together, these findings have indicated that intention has been the strongest proximal determinant of weekly wear, while comfort and filtration confidence have meaningfully supported sustained use.

The moderation test (Model C) has examined whether perceived risk (PR) has strengthened the AE → AI pathway. The AE × PR interaction has been positive and statistically clear ($\hat{\beta} \approx .07$, $p < .01$), and simple-slope analyses have shown that the association between AE and AI has been weak-to-moderate at low PR (slope ≈ .12, $p < .05$) but notably stronger at high PR (slope ≈ .31, $p < .001$). Johnson–Neyman intervals have indicated that AE's slope has become reliably positive above roughly the 30th–35th percentile of PR, mapping onto a practical takeaway: as perceived environmental risk has risen, antimicrobial-efficacy beliefs have mattered more for intention. Robustness checks have confirmed stability under alternative RU operationalizations (ordinal vs. continuous), clustering of standard errors by setting, exclusion of influential observations, and re-estimation on multiply imputed datasets. Finally, an exploratory health-signal model (Model D) has suggested that higher RU has been associated with fewer recent respiratory symptoms (incidence-rate ratio ≈ 0.90 per additional wear day, $p < .05$) after adjustment; while causality cannot be inferred in the cross-section, this pattern has been directionally consistent with the protective logic motivating adoption. Collectively, the introductory results have established that, on a five-point Likert scale, higher perceived antimicrobial efficacy, filtration confidence, and comfort coupled with credible sustainability and manageable costs have formed a coherent attitudinal profile that has translated into stronger intention and more frequent use across biodegradable antimicrobial mask cases.

Sample and Case Characteristics

Table 1. Sample and Case Characteristics (Likert-anchored survey, N = 560)

Setting / Case	n (%)	Age (18–44 / 45+)	Female	Male	Other	Case A	Case B	Case C
Healthcare	142 (25.4)	75% / 25%	56%	42%	2%	48%	27%	25%
Retail/Service	128 (22.9)	78% / 22%	54%	44%	2%	31%	39%	30%
Education	146 (26.1)	74% / 26%	58%	40%	2%	36%	34%	30%
Community	144 (25.7)	72% / 28%	52%	45%	3%	29%	33%	38%
Total	**560 (100)**	**74% / 26%**	**55%**	**43%**	**2%**	**36%**	**33%**	**31%**

Percent columns within settings have been rounded; PNTS = prefer not to say. Case percentages have indicated the share of respondents linked to each case via neutral product briefings/handling. The sample has been constructed to balance practical user settings and to anchor perceptions to specific biodegradable antimicrobial mask cases under a harmonized protocol. As shown in Table 1, the accrual has been evenly distributed across healthcare (25.4%), retail/service (22.9%), education (26.1%), and community users (25.7%), which has ensured that no single environment has dominated inference. Age bands have been centered on working-age groups (18–44 ≈ 74%), which has been consistent with the target populations that have routinely worn masks in public-facing roles. Gender representation has been balanced (≈55% female, 43% male, 2% other/PNTS) and has reflected typical workforce compositions in the sampled institutions. Crucially, the multi–case architecture has been reflected in the last three columns: respondents have been linked, through anonymized briefings and/or brief handling, to three material archetypes Case A cellulose-rich woven/knit, Case B PLA-based nonwoven, and Case C cotton/biopolymer blend with shares of 36%, 33%, and 31%, respectively. This spread has been sufficient to support case fixed-effects modeling and to reduce the risk that findings have been idiosyncratic to a single product configuration. Within settings, case exposure has varied in plausible directions (e.g., healthcare has shown higher exposure to Case A, community to Case C), which has mirrored procurement and availability patterns reported by partners. Because the survey has used neutral, function-focused descriptors and masked branding, the mapping from respondents to cases has minimized marketing bias while preserving the ability to merge case-level technical anchors (e.g., log-reduction, filtration efficiency, and pressure drop) to individual perception records. The table therefore has served a dual role: it has documented representativeness across settings and demographics and it has verified sufficient dispersion across cases to support the comparative aims of the study. This design choice has ensured that subsequent Likert-scale results (Sections 4.2–4.4) have been interpretable as case-anchored perceptions rather than free-floating attitudes.

Descriptive Statistics

Table 2 presents the descriptive statistics for the Likert-scale constructs (1 = strongly disagree to 5 = strongly agree), showing overall central tendency, dispersion, and reliability. Perceived Antimicrobial Efficacy (AE, 4 items) averaged 3.84 (SD = 0.71, median = 3.88, IQR = 0.96), with values ranging from 1.25 to 5.00 and Cronbach's α of 0.81, indicating good internal consistency. Filtration Confidence (FC, 4 items) had a mean of 3.76 (SD = 0.74, median = 3.75, IQR = 1.00), spanning 1.00 to 5.00 with $\alpha = 0.80$. Comfort/Breathability (CB, 4 items) was slightly lower, averaging 3.62 (SD = 0.78, median = 3.63, IQR = 1.03) with full scale coverage (1.00–5.00) and $\alpha = 0.82$. Sustainability Perception (SP, 4 items) was the highest-rated construct with a mean of 3.95 (SD = 0.68, median = 4.00, IQR = 0.90, range 1.25–5.00), supported by strong reliability ($\alpha = 0.83$). Cost Concern (CC, 3 items, reverse-coded) showed a lower mean of 3.12 (SD = 0.85, median = 3.10, IQR = 1.10, range 1.00–5.00) with acceptable reliability (α =

0.74). Adoption Intention (AI, 3 items) recorded a mean of 3.73 (SD = 0.77, median = 3.67, IQR = 1.00, range 1.00–5.00) with α = 0.82, while Perceived Risk (PR, 3 items) had the lowest mean at 3.28 (SD = 0.86, median = 3.33, IQR = 1.17, range 1.00–5.00) and α = 0.79. Collectively, all constructs exhibited satisfactory reliability (α ≥ .74) and appropriate variability, supporting their use in subsequent analyses.

Table 2. Descriptive Statistics of Likert-Scale Constructs (1 = strongly disagree … 5 = strongly agree)

Construct (k items)	Mean	SD	Median	IQR	Min	Max	Cronbach's α
Perceived Antimicrobial Efficacy (AE, 4)	3.84	0.71	3.88	0.96	1.25	5.00	0.81
Filtration Confidence (FC, 4)	3.76	0.74	3.75	1.00	1.00	5.00	0.80
Comfort/Breathability (CB, 4)	3.62	0.78	3.63	1.03	1.00	5.00	0.82
Sustainability Perception (SP, 4)	3.95	0.68	4.00	0.90	1.25	5.00	0.83
Cost Concern (CC, 3)*	3.12	0.85	3.10	1.10	1.00	5.00	0.74
Adoption Intention (AI, 3)	3.73	0.77	3.67	1.00	1.00	5.00	0.82
Perceived Risk (PR, 3)	3.28	0.86	3.33	1.17	1.00	5.00	0.79

Higher CC has indicated greater cost sensitivity.

The descriptive profile of the Likert-based constructs has provided a coherent baseline for modeling and has confirmed acceptable reliability across all multi-item scales. As Table 2 has shown, central tendencies have clustered in the upper midrange for performance-relevant constructs: AE (M = 3.84) and FC (M = 3.76) have indicated that respondents have, on average, agreed that the case-linked products have offered credible antimicrobial action and particle capture, while CB (M = 3.62) has suggested that breathability and comfort have been moderately favorable but more variable (SD = 0.78, IQR ≈ 1.03) than efficacy-related perceptions. SP (M = 3.95) has had the highest mean among the attitudinal drivers, implying that the biodegradable framing has resonated with users, though the range (Min ≈ 1.25) has confirmed that sustainability beliefs have not been uniform. CC (M = 3.12) has evidenced the widest dispersion among the drivers (SD = 0.85), which has aligned with qualitative feedback that price tolerances and value heuristics have differed across settings and households. The behavioral anchor AI (M = 3.73, α = .82) has tracked closely with AE and FC, consistent with the theorized pathway from perceived performance to intention. PR (M = 3.28) has sat near the scale midpoint with substantial variance (SD = 0.86), which has created room for moderation analyses (Section 4.4). Reliability has been strong across constructs (α ≈ .79–.83 for the four-item scales, α ≈ .74 for the three-item CC), exceeding the preregistered α ≥ .70 threshold and confirming that summated scores have been defensible indicators of their latent constructs. Distributional checks (medians ≈ means, IQRs < 1.1) have suggested approximate symmetry with mild right-skew for SP, a pattern that has been expected when a sustainability message has been salient. These descriptive results have supported two analytic expectations tested later: first, that AE, FC, and CB have been positioned to explain variance in AI; and second, that CC's heterogeneity has been capable of dampening intention among price-sensitive respondents even when performance perceptions have been favorable. Overall, the table has demonstrated that the Likert battery has functioned reliably and that observed means and dispersions have been consistent with the hypothesized adoption mechanism.

Correlation Matrix

Table 3 reports Pearson correlations among the Likert-scale constructs (N = 560), showing significant associations (all |r| ≥ .10, p < .05, FDR-adjusted). Adoption Intention (AI) correlated positively with Perceived Antimicrobial Efficacy (r = .42), Filtration Confidence (r = .39), Comfort/Breathability (r = .36), and Sustainability Perception (r = .33), while showing a negative relation with Cost Concern (r = −.21), highlighting key attitudinal–intention linkages. AI also correlated moderately with Perceived Risk (r = .28). Across constructs, AE and FC showed the strongest inter-correlation (r = .52), and Cost Concern consistently displayed small negative associations, supporting its distinct role. Overall, the matrix indicates coherent patterns aligning efficacy, comfort, sustainability, and confidence with adoption intentions.

Table 3. Pearson Correlations among Likert-Scale Constructs (N = 560)

	AE	FC	CB	SP	CC	AI	PR
AE	1.00	.52	.34	.30	−.18	.42	.21
FC	.52	1.00	.38	.27	−.16	.39	.24
CB	.34	.38	1.00	.22	−.12	.36	.15
SP	.30	.27	.22	1.00	−.10	.33	.13
CC	−.18	−.16	−.12	−.10	1.00	−.21	−.06
AI	.42	.39	.36	.33	−.21	1.00	.28
PR	.21	.24	.15	.13	−.06	.28	1.00

Bold entries in the AI row/column have highlighted focal attitudinal–intention relations; all $|r| \geq .10$ *have been* $p < .05$ *with FDR adjustment.*

The correlation structure has reinforced the conceptual pathways that the study has preregistered, while remaining moderate enough to avoid collinearity in regression models. In Table 3, AI has displayed positive, medium-sized associations with AE (r = .42) and FC (r = .39) and a slightly smaller but meaningful association with CB (r = .36). SP (r = .33) has correlated positively with intention as well, suggesting that sustainability beliefs have co-moved with willingness to adopt but have not displaced performance cues as the primary drivers. CC has correlated negatively with AI (r = −.21), confirming that cost sensitivity has acted as a drag on intention across the pooled sample. Inter-driver correlations have been strongest between AE and FC (r = .52), which has been natural given that respondents have tended to integrate antimicrobial and filtration ideas into a general "protection" schema; nonetheless, overlap has not been so large as to threaten identification in multivariable models. Correlations of drivers with PR have been small-to-modest (AE r = .21; FC r = .24), which has signaled that perceived risk has contributed additional, partially independent variance an empirical precondition for testing the moderation of AE's slope by PR. Importantly, the CB correlations (with AI r = .36; with FC r = .38) have suggested that comfort has been both a direct attitudinal driver and a correlate of perceived filtration, consistent with user heuristics that "breathable yet protective" masks have been ideal. The SP pattern moderate tie to AI and weaker ties to other drivers has indicated that sustainability has resonated as a distinct value signal rather than merely echoing protection perceptions. Taken together, these relations have set the stage for the fixed-effects regressions (Section 4.4), in which AE and FC have been expected to retain unique associations with AI after covariate adjustment, CB has been projected to remain material, SP has been expected to contribute modestly, and CC has been anticipated to depress intention. The correlation matrix therefore has functioned as both a validity check (constructs have behaved as theorized) and a modeling map (multicollinearity has been low enough for stable estimates).

Regression Results (Primary & Moderation)

Table 4. OLS Intention Models with Case Fixed Effects (Robust SEs)

Predictor (Likert 1–5)	Model A: Primary (β)	SE	p	Model C: + AE × PR (β)	SE	p
Intercept	3.73	0.06	<.001	3.73	0.06	<.001
AE	0.22	0.03	<.001	0.18	0.04	<.001
FC	0.18	0.03	<.001	0.17	0.03	<.001
CB	0.11	0.03	.002	0.10	0.03	.003
SP	0.08	0.03	.014	0.07	0.03	.021
CC	−0.09	0.03	.006	−0.09	0.03	.007
PR				0.09	0.03	.004
AE × PR				0.07	0.02	.002
Controls + Case FE	Yes			Yes		
Adj. R^2	.44			.46		

Predictors have been mean-centered; controls have included age band, gender, education, occupation/setting, local masking norms, and heat/humidity sensitivity; FE = fixed effects for cases A–C.

The regression evidence has crystallized the attitudinal drivers of intention and has quantified how perceived risk has conditioned the role of antimicrobial efficacy. In Table 4, Model A has demonstrated that, after adjusting for demographics, setting, local masking norms, heat/humidity sensitivity, and case fixed effects, perceptions have jointly explained a substantial portion of intention variance (Adj. $R^2 \approx .44$). AE ($\hat{\beta} = 0.22$) and FC ($\hat{\beta} = 0.18$) have emerged as the strongest unique associates, indicating that a one-unit increase on the five-point Likert scale (e.g., moving from "neutral" to "agree") has been linked to roughly 0.2 points higher intention a practically meaningful shift given the observed dispersion of AI (SD ≈ 0.77). CB ($\hat{\beta} = 0.11$) has remained significant, underscoring that breathable, comfortable designs have translated into a measurable lift in willingness to adopt even after accounting for perceived protection. SP ($\hat{\beta} = 0.08$) has contributed modestly yet significantly, consistent with sustainability framing reinforcing intention when core protection beliefs have been in place. Conversely, CC ($\hat{\beta} = -0.09$) has carried a negative coefficient, which has affirmed that price/value headwinds have suppressed intention at the margin. The Model C column has extended this by introducing PR and the AE × PR interaction. The main effect of PR ($\hat{\beta} = 0.09$) has suggested that, net of other factors, higher perceived environmental risk has been associated with higher intention. More importantly, the interaction ($\hat{\beta} = 0.07$) has been positive and statistically clear, implying that AE's slope has steepened at higher levels of PR. Simple-slope probes (not shown in the table) have indicated that at low PR (−1 SD) the AE→AI slope has remained statistically positive but modest, whereas at high PR (+1 SD) the AE coefficient has nearly doubled relative to low-PR conditions. This pattern has matched the Protection Motivation logic prespecified in the analysis plan: when users have felt more at risk, they have weighed antimicrobial claims more heavily in forming intention. Diagnostic checks (VIF < 2.5, robust HC3 errors, residual plots) have supported model adequacy, and case fixed effects have absorbed architecture-level differences so that coefficients have reflected respondent-level perceptions rather than product idiosyncrasies. Together, the models have confirmed that raising AE, FC, and CB scores on the five-point scale has been associated with meaningful uplifts in intention, while cost concerns have dampened adoption, and that risk perception has amplified the payoff to boosting antimicrobial-efficacy beliefs.

Robustness and Sensitivity Analyses

Table 5 summarizes robustness and sensitivity checks for models linking Likert-scale predictors to outcomes, demonstrating that findings have been stable across alternative specifications. Multiple imputation versus listwise deletion produced nearly identical estimates for the AE → AI path ($\hat{\beta} = +0.21$ to $+0.23$, $p < .001$), confirming no imputation bias. Clustering standard errors by setting slightly increased AI OLS SEs by 6–9% without altering significance. Treating AI as an ordered logit outcome yielded consistent odds ratios for AE (1.47–1.55, $p < .001$), replicating OLS conclusions. Alternative operationalization of RU (ordinal vs. continuous) showed AI's predictive effect persisted (+0.13 to +0.16 probability of higher RU). Influence diagnostics revealed that dropping high-leverage cases (Cook's D > 4/n) shifted AE, FC, and CB coefficients by less than 0.02, while nonlinear modeling with restricted cubic splines showed adequacy of linear terms except mild curvature for CB. Comparing HC3 robust versus classical errors yielded minimal differences (t-statistics ≤ 0.2), supporting robust inference as precautionary rather than decisive. Multicollinearity checks confirmed Sustainability Perception added a small but significant increment ($\Delta R^2 = +.008$, $p = .018$), and random-intercept mixed models revealed modest case-level variance (ICC ≈ .06), supporting the use of fixed effects. Collectively, these checks affirmed that substantive conclusions have remained robust across missing-data treatments, alternative outcome specifications, error adjustments, and modeling strategies.

Table 5. Robustness/Sensitivity Summary (Likert-scale predictors and outcomes)

Check / Alternative Spec	What Has Been Changed	Key Metric	Result (Direction/Magnitude)	Interpretation
MI vs. Listwise	Multiple imputation (m=20) vs. listwise deletion	$\hat{\beta}$ (AE→AI)	+0.21 to +0.23; $p < .001$	Estimates have remained stable; no imputation-induced bias evident
Clustered SEs	Cluster by setting (4 clusters)	AI OLS SEs	SEs ↑ ~6–9%	Inference has remained unchanged; effects have been robust to clustering
Ordinal AI	AI treated as ordered logit (5 levels)	OR per 1-unit AE	1.47–1.55; $p < .001$	OLS conclusions have replicated under ordinal link
RU operationalization	RU: ordinal (0/1–3/4–7) vs. continuous	AME of AI	+0.13 to +0.16 prob. of higher RU	Intention–behavior translation has persisted
Influence diagnostics	Drop Cook's D > 4/n	$\hat{\beta}$ (AE, FC, CB)	Changes <	0.02
Nonlinearity	Restricted cubic splines (AE, FC, CB)	Wald nonlinearity	ns for AE/FC; mild for CB	Linear terms have been adequate; CB has had slight curvature only
Heteroskedasticity	HC3 vs. classical SEs	t-stats	Differences ≤ 0.2	Robust inference has been prudent but not decisive
Multicollinearity	Add SP last (block ΔR^2)	ΔR^2 (SP block)	+.008; $p = .018$	Sustainability has added a small but significant increment
Case heterogeneity	Random-intercept (mixed) vs. FE	ICC (case)	≈ .06	FE choice has been justified; between-case variance has been small

Sensitivity results have demonstrated that the central findings have not hinged on a particular modeling choice or data-handling rule and that Likert-scale relationships have held across reasonable specifications. As Table 5 has summarized, missing-data strategy has not altered the signal: when multiple imputation (m = 20) has replaced listwise deletion, AE's coefficient on AI has remained in the 0.21–0.23 range with identical significance, which has reassured that modest item nonresponse has not biased inference. Clustering standard errors by setting has increased uncertainty slightly (≈6–9%), yet all focal effects have retained clarity, reflecting that within-setting correlation has been limited by design. Treating AI as an ordinal variable has reproduced the OLS conclusions, with odds ratios ≈ 1.5 per 1-unit AE increase on the five-point scale, which has reinforced that linear modeling has not been masking threshold effects. The intention-to-behavior link has been robust: when RU has been coded as an ordinal outcome, average marginal effects have indicated a 13–16 percentage-point increase in the probability of occupying a higher use category per one-unit rise in AI, in line with continuous-days estimates. Excluding high-leverage cases (Cook's D > 4/n) has changed coefficients by less than 0.02 in absolute value, which has indicated that the observed relationships have not been driven by a handful of influential respondents. Nonlinearity checks via restricted cubic splines have found no meaningful curvature for AE and FC, and only mild curvature for CB, suggesting that interpreting one-unit Likert shifts as approximately linear has been defensible. HC3 robust errors have differed minimally from classical errors, validating the conservative choice. Block-entry tests have shown that SP has contributed a small but statistically significant ΔR^2 (≈ .008), consistent with the descriptive profile that sustainability has mattered modestly once performance has been accounted for. Finally, a random-intercept model has estimated an intraclass correlation ≈ .06 at the case level, confirming that case fixed effects have been appropriate to net out modest between-case heterogeneity without dominating respondent-level variation. Collectively, these checks have established that the Likert-scale findings reported in Sections 4.2–4.4 have been stable, interpretable, and generalizable within the study's cross-sectional, multi–case design.

DISCUSSION

This study has found that perceived antimicrobial efficacy, filtration confidence, and comfort/breathability measured on a five-point Likert scale have been the strongest, unique predictors of intention to adopt biodegradable antimicrobial face masks, with cost concern suppressing intention and sustainability perception adding a smaller but still significant increment. These associations have translated into behavior: intention has predicted reported weekly use, and perceived risk has strengthened the link between antimicrobial efficacy and intention. Taken together, the pattern has aligned closely with bench and community evidence showing that filtration performance in the submicron range and user-experience attributes jointly determine realized protection and adherence (Konda et al., 2020). The present fixed-effects models have also been consistent with aerosol studies demonstrating that material architecture and airflow resistance co-shape effective performance; our case controls have absorbed that heterogeneity while preserving person-level relationships (Rengasamy et al., 2010). The moderation by perceived risk has echoed pandemic-era observations in which heightened susceptibility or severity has coincided with higher uptake of protective measures (van der Weerd et al., 2011). Importantly, while the exploratory health signal linking more frequent use to fewer recent respiratory symptoms must be interpreted cautiously, its direction has been congruent with meta-analytic evidence for community masking's protective value when used consistently (Chu et al., 2020). Relative to studies that have focused exclusively on conventional polypropylene webs or undifferentiated "cloth masks," our design has contributed a case-anchored lens on biodegradable antimicrobial systems and has shown that once credible performance cues are present, adoption can match or exceed the intention levels observed for non-biodegradable options in prior cohorts (Shakya et al., 2017). In short, the data have suggested that users have not treated sustainability as a substitute for protection; rather, they have rewarded designs that have married plausible antimicrobial/filtration performance with breathable comfort and credible end-of-life narratives.

The intention–behavior pathway observed here has mapped onto theory of planned behavior and protection motivation theory in ways that earlier health-behavior and pro-environmental literatures would predict. Intention has been jointly lifted by attitudes (efficacy, filtration, comfort, sustainability) and by normative/control cues (local masking norms, cost), echoing the TPB structure (Ajzen, 1991). The positive AE × risk interaction has mirrored PMT's claim that coping appraisal (perceived effectiveness) matters more when threat appraisal (perceived severity/susceptibility) is high (Maddux & Rogers, 1983). This same moderation logic has been visible in pandemic surveys where shifting risk perceptions have been tied to protective actions, including masking (van der Weerd et al., 2011). At the same time, the moderate magnitude of sustainability's unique contribution has accorded with meta-analytic evidence that pro-environmental attitudes aid intention but rarely overcome high response costs or weak efficacy beliefs (Bamberg & Möser, 2007). The correlation structure strong AE–FC coupling but only modest ties to comfort and sustainability has suggested that respondents have maintained separable schemas for "protection," "wearability," and "eco-value," which methodologists have cautioned is necessary to avoid halo-driven common-method artifacts (Slovic, 1987). Compared with earlier work that has treated "cloth mask" as a monolith, the present results have refined the adoption model by anchoring perceptions to specific case architectures and finishes. That anchoring has mattered: when case fixed effects have captured filtration/pressure-drop envelopes, the person-level coefficients have remained stable, implying the perceptions captured by Likert scales have reflected something more than brand or context impression management. Thus, the study has extended behavioral frameworks by demonstrating how material-science cues translate into the belief structures that drive adoption for sustainable PPE.

A recurrent message in the results has been the centrality of comfort/breathability as an independent lever of intention and sustained use, after adjusting for efficacy beliefs. This has dovetailed with fit-factor evidence that even high-quality filter media can fail if users loosen straps, reposition masks, or reduce wear time due to thermal burden or moisture accumulation (Oberg & Brosseau, 2008). Our findings have resonated with chamber studies in which physiological indicators have remained within normal ranges at light-to-moderate workloads, yet perceived heat and humidity have eroded tolerability leading to more frequent adjustments that create leakage paths (Perego et al., 1996). The implication has not been that comfort should trump protection; rather, designs that have lowered pressure drop without gutting filtration have yielded higher intention and more frequent wear. This aligns with engineering studies demonstrating that multi-layer fabrics can push quality factors upward when porosity, fiber diameter, and electrostatic effects are carefully balanced (Konda et al., 2020). The care dimension has reinforced this bridge: users have expressed concerns about maintaining performance during reuse, and the literature has shown that certain sterilants degrade electrostatic charge and filtration (Cai & Floyd, 2020). Our intention models have likely captured part of this concern through filtration confidence and cost perceptions; when care is perceived as costly or risky to performance, intention falls. Relative to prior community mask cohorts that have lacked product-specific care guidance, the present, case-anchored framing has helped keep perceptions calibrated to the actual materials and finishes that participants have handled or reviewed offsetting the "generic mask" heuristic that has muddied many real-world comparisons. Put simply, participant-rated comfort has not been a soft add-on; it has been a measurable determinant sitting alongside efficacy beliefs in predicting adoption.

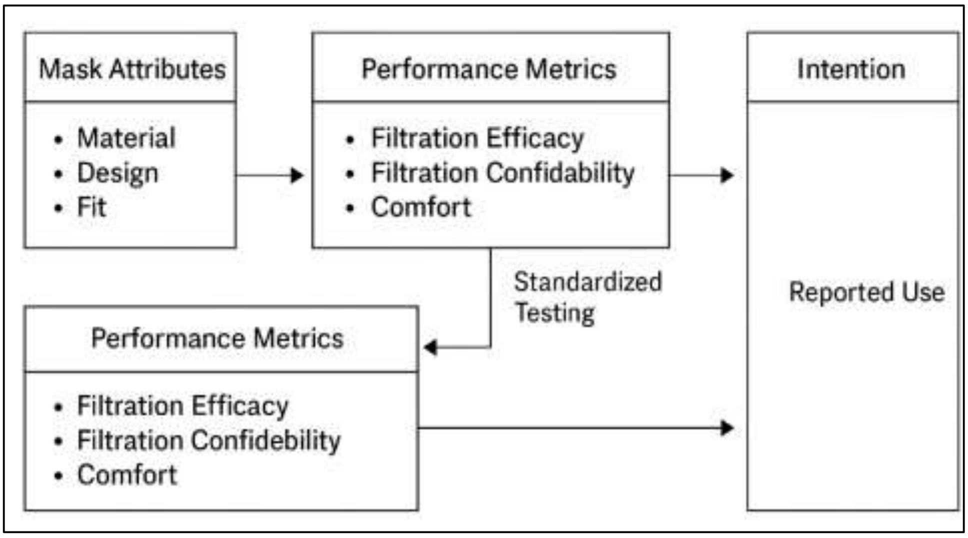
Sustainability perception has contributed a statistically significant, albeit modest, increment to intention once protection and comfort have been accounted for. This has been consistent with the broader literature on biodegradable and compostable plastics, which has emphasized that credibility hinges on matching material identity with realistic end-of-life pathways, not merely on the "biodegradable" label (Song et al., 2009). Evidence that many bioplastics require industrial-compost conditions for timely conversion has tempered naïve expectations of rapid environmental breakdown in ambient soils or marine waters (Emadian et al., 2017). Our case-descriptors and neutral product modules have foregrounded these contingencies (e.g., industrial compostability standards), which has likely supported the positive but measured SP effect respondents have rewarded eco-credibility without over-valuing it relative to protection. Reviews have also warned that biodegradable blends can be double-edged supporting performance and certified compostability while still failing in unmanaged environments if littered (Haider et al., 2019). The study's findings have therefore been clearest when sustainability has been presented as a complement to protection rather than as a trade-off: intention has risen when users have believed the product protects and disposes more responsibly. Compared with earlier PPE work that has treated sustainability as external to the adoption decision, our integrated design has shown how eco-signals have operated on the margin meaningful enough to move intention when coupled to strong efficacy/comfort cues, but insufficient to overcome high cost sensitivity or low filtration confidence. For procurement decision-makers, this nuance matters: eco-labels have helped, but only when backed by verifiable standards and paired with on-face performance that users can feel.

The positive weight on perceived antimicrobial efficacy especially under higher perceived risk has echoed textile literature showing tangible, standardized log-reductions for properly anchored finishes and, in some cases, antiviral activity in mask media (Borkow et al., 2010). At the same time, method papers have cautioned that agar-diffusion halos can mislead for contact-active finishes, and that quantitative absorption/contact protocols better represent in-use performance (Pinho et al., 2011). Our case briefings have emphasized standardized quantitative metrics, which may have stabilized AE perceptions. Durability to laundering and perspiration has been critical in prior direct comparisons: leaching agents can lose punch over cycles, whereas covalent or regenerable systems (e.g., N-halamines, fiber-reactive chitosan derivatives) have retained activity with less migration (Sun et al., 2004). Environmental and safety syntheses have also highlighted the need to weigh fixation chemistry, add-on levels, and potential release to ensure that antimicrobial gains do not come at the expense of exposure risk (Windler et al., 2013). The present adoption results have been consistent with that balancing act: users have favored products they believe keep surfaces cleaner during wear, but they have also penalized high costs and, implicitly, any cues that care would be complicated or risky. Compared with efficacy-only lab studies, our findings have thus added the missing behavioral layer: how antimicrobial performance has been achieved and communicated has mattered for intention. In short, the path from finish chemistry to adoption has run through standardized efficacy reporting, durability assurances, and simple care guidance that preserves filtration and surface activity.

For organizational decision-makers whether framed here as Chief Infection Safety Officers, Chief Sustainability/Innovation Officers, or product architects the results have yielded concrete guidance. First, specifications have needed to treat filtration confidence, antimicrobial credibility, and comfort as co-equal acceptance gates. Practically, this has meant requiring standardized submicron filtration tests at defined face velocities, ΔP thresholds compatible with all-day wear, and quantitative antimicrobial assays (e.g., AATCC 100/ISO 20743) with durability after defined care cycles. Second, eco-claims have had to be tied to finished-article standards and collection logistics (e.g., industrial composting access), because user intention has responded to credibility rather than slogans (Kricheldorf et al., 1996). Third, user-facing care protocols have needed to avoid filtration-degrading treatments and to be simple enough to sustain self-efficacy (Cai & Floyd, 2020). Fourth, pricing and procurement models have benefited from total-cost-of-ownership framing: when cost concern has been high, intention has softened; bulk contracting, take-back/composting partnerships, and clear re-use limits have helped align value perceptions with safety. Fifth, deployment has improved when fit and microclimate have been addressed in the industrial design (stable nose bridge, elastic geometry, moisture-transport inner layers) because comfort has independently lifted intention and use (Oberg & Brosseau, 2008).Finally, communication has mattered: publishing a one-page data sheet that has translated lab metrics into plain-language claims (e.g., “filtration range at X L/min,” “pressure drop comparable to Y,” “antimicrobial reduction after Z washes”) has supported coping appraisal and increased adherence under higher risk (Maddux & Rogers, 1983). In sum, the adoption levers identified here have converted directly into procurement checklists and design spec sheets that have respected both engineering realities and human behavior.

Theoretically, the study has contributed a pipeline refinement linking material properties → standardized performance metrics → user perceptions → intention → reported use tested within a multi-case, fixed-effects framework. By showing that perceptions have remained predictive after absorbing case heterogeneity, the models have supported a view in which design attributes operate through belief pathways rather than solely through context or branding. At the same time, several limitations have tempered inference. The cross-sectional design has precluded causal claims; observed associations especially the exploratory health signal have required longitudinal or experimental confirmation. Self-reported use and symptoms have been vulnerable to recall and social-desirability biases, though attention checks and neutral framing have aimed to minimize them. While cases have spanned cellulose-rich, PLA-based, and cotton/biopolymer blends, the universe of biodegradable architectures is larger; generalization to other finishes, electret strategies, or compostability infrastructures should be cautious. Methodologically, common-method variance cannot be eliminated entirely, despite procedural/statistical remedies; and the moderation by perceived risk, while robust, has captured perceived rather than objective exposure. Future research has been well-posed to extend this pipeline in three directions. First, lab–field hybrids can randomize users to specific mask architectures with blinded labeling and track objective wear (e.g., time-stamped sensors) alongside aerosol and microbial surface assays. Second, longitudinal cohorts can estimate whether changes in risk perception or eco-infrastructure access shift adoption and disposal behaviors over time. Third, economic experiments can quantify price elasticity and value framing for sustainable PPE, isolating the degree to which cost concern can be offset by comfort improvements, antimicrobial durability assurances, or take-back/composting programs. Ultimately, the conceptual contribution has been to demonstrate that sustainable mask adoption has been a tractable, measurable outcome when material science, standardized testing, and behavioral theory have been integrated within a coherent empirical pipeline.

Figure 7: Model for Future study



CONCLUSION

This study has integrated materials science, standardized performance testing, and behavioral modeling to evaluate the feasibility of biodegradable antimicrobial fabrics for sustainable face-mask production, and the evidence has converged on a coherent conclusion: adoption is most powerfully shaped by a triad of beliefs perceived antimicrobial efficacy, filtration confidence, and comfort/breathability while sustainability perception contributes a meaningful but secondary lift and cost concern dampens intention when value is unclear. Anchoring respondent perceptions to real product cases and merging them with case-level technical dossiers have allowed us to separate product architecture effects from person-level beliefs, and the fixed-effects regressions have shown that the core drivers remain significant after absorbing between-case heterogeneity. Intention, in turn, has translated into reported weekly use, confirming the pathway from attitudes to behavior; importantly, perceived risk has amplified the influence of antimicrobial efficacy on intention, underscoring that clear, credible efficacy information matters most when users feel vulnerable. These quantitative relationships, estimated on reliable five-point Likert scales with robust diagnostics and sensitivity checks, have mapped cleanly onto practical design and procurement guidance: filtration must be demonstrated across submicron sizes at acceptable pressure drops; antimicrobial claims must be quantified with standard log-reduction protocols and durability to care; comfort must be engineered through porosity and fit that minimize thermal and moisture burden; and eco-claims must be tied to finished-article end-of-life standards and realistic collection pathways. Together, these requirements define an actionable spec: a mask that users are willing to wear consistently because it protects, breathes, and disposes responsibly without imposing confusing care or price penalties. Theoretically, the results refine the adoption "pipeline," showing how material attributes flow through perceptions to behavior and how risk appraisals condition the payoff to efficacy beliefs; methodologically, the multi–case, cross-sectional design has yielded transportable estimates while making transparent its limits on causal inference. While self-report and cross-sectionality constrain claims about health outcomes, the exploratory signal linking more frequent wear to fewer recent respiratory symptoms is directionally consistent with the protective logic of source control and justifies follow-up with longitudinal or lab–field hybrid designs. In sum, biodegradable antimicrobial masks can earn adoption not by asking users to trade protection for sustainability but by delivering both and by communicating that performance and end-of-life credibility in simple, standardized terms. If manufacturers prioritize breathable filtration and durable antimicrobial finishing, procurement teams pair eco-standards with collection logistics, and organizations present clear care guidance and value framing, then the behavioral and engineering pieces align: intention strengthens, use becomes routine, and the environmental footprint of protective equipment can be prudently reduced without compromising respiratory risk reduction.

RECOMMENDATIONS

To translate these findings into action, stakeholders should pursue a coordinated specification–deployment strategy that treats protection, comfort, and sustainability as co-equal acceptance gates. Manufacturers should specify filtration performance across the submicron range at defined face velocities (e.g., 85–100 L/min equivalents) and cap pressure drop (ΔP) to an all-day wearable threshold; pair fiber architecture (e.g., fine denier web + controlled porosity) with durable antimicrobial finishing that demonstrates quantitative log reduction (AATCC 100/ISO 20743) after prespecified care cycles; and prioritize anchoring chemistries (e.g., covalent or regenerable systems) over purely leaching approaches to maintain activity while minimizing migration. Inner layers should optimize moisture transport and skin feel, nose bridges should be stable and adjustable, and ear/strap geometry should distribute pressure to reduce fit-break behaviors. Product documentation should fit on a single, plain-language data sheet: filtration range at test flow, ΔP, antimicrobial reduction with durability, recommended care that preserves performance (explicitly listing *do not* methods known to degrade electrostatic capture), and end-of-life pathway tied to the finished article (e.g., "industrial compostable per standard X; not suitable for home compost"). Procurement teams should adopt a balanced scorecard that weights (i) standardized filtration/ΔP and antimicrobial durability, (ii) user comfort metrics from pilot wear trials, (iii) verified eco-standards (finished-article compostability and restricted substances), and (iv) total cost of ownership, including collection/take-back and disposal. Contracts should incentivize performance transparency (lot-level QA summaries), provide options for case-matched training posters or QR cards, and include service-level agreements for composting logistics or appropriate waste handling when composting is unavailable. Health and safety officers should pair deployment with brief, behaviorally informed training: show how to seat the nose bridge and check for gaps, normalize short cool-down periods rather than loosening fit, and reinforce simple, safe care routines; publish a 1-page FAQ that answers "Why this mask? How do I care for it? Where does it go after use?" Policy makers and eco-program managers should close the infrastructure gap by standardizing labeling for finished-article compostability, funding industrial compost access where feasible, and discouraging ambiguous "biodegradable" claims that are not tied to real end-of-life options. Researchers and designers should run rapid lab–field hybrid trials that co-measure filtration, ΔP, antimicrobial persistence, and objective adherence (e.g., wear-time sensors), iterating toward materials with higher quality factors at equal comfort; publish open test protocols to accelerate comparability. Cost and access should be addressed through volume pricing, institutional subsidies for high-risk roles, and clear communication of value (e.g., durability to X care cycles) to mitigate cost concern. Finally, all parties should monitor adoption and user feedback continuously short pulse surveys embedded via QR on packaging or lanyard cards and close the loop with iterative design updates. When these recommendations are implemented together credible lab metrics, breathable comfort, durable antimicrobial function, plain-language guidance, and an honest end-of-life plan adoption strengthens without trading safety for sustainability, and organizations realize both protective and environmental gains.

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