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Development of KF-Rated Face Mask Using Biodegradable and Functional Materials

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Abstract: The widespread use of disposable masks during the COVID-19 pandemic has led to a sharp increase in plastic waste, mainly due to the non-biodegradable polypropylene materials used in conventional mask production. This study aimed to develop an eco-friendly Korean filter-certified health mask using biodegradable polylactic acid fibers and natural materials. The traditional synthetic components of the outer, filter, and inner layers of the mask were replaced with sustainable alternatives. In addition, antibacterial and deodorizing properties were enhanced using jade-based coatings. Performance tests confirmed the filtration efficiency and breathability of the mask. The mask achieved over 70% biodegradability and decomposed within 45 days in composting environments, leading to a lower environmental impact than conventional masks. In addition, wearability assessments indicated significantly improved comfort, particularly in terms of breathability and hygiene. This study highlights the potential of sustainable mask production and its role in addressing plastic waste. This study presents a sustainable alternative to maximize the biodegradability of mask materials, thereby reducing carbon emissions and landfill burdens after disposal. This work reflects the social responsibility towards environmental issues through the use of eco-friendly materials and has implications for increasing the demand for sustainable products.

Keywords: biodegradable mask; KF certification; PLA fiber; eco-friendly materials; sustainability

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1. Introduction

Masks are one of the most recognizable objects of the COVID-19 era due to their critical role in mitigating transmission, leading to their unprecedented consumption [1]. Disposable masks are generally made of nonwoven fabrics and melt-blown (MB) filters bonded together several times to protect against particulate matter and droplet infections. They filter contaminated air through a filtering surface rather than supplying clean air [2]. The length of time a disposable mask should be worn and used depends on the performance of the product, but four hours is generally recommended, and reuse is not advised [3]. Therefore, most disposable masks are single use [4], thus contributing to a negative environmental impact, particularly because polypropylene (PP), the main material of masks, requires 450 years to fully degrade in the ground through microbial activity [5]. In 2021, 20 million disposable masks were disposed of daily around the world, amounting to 7.3 billion per year. These were mainly sent to landfills and incinerators, without any recycling.

To address these issues, in 2021, the National Human Rights Commission prepared a policy proposal on "Eco-friendly Use and Disposal of Disposable Masks", which was

submitted to the Ministry of Environment, Ministry of Food and Drug Safety, Korea Centers for Disease Control and Prevention, and Ministry of Education. In addition, standard guidelines for the production and distribution of eco-friendly masks were prepared and disseminated to manufacturers, and the committee urged the Ministry of Environment to provide administrative and financial support for the production and distribution of masks made of eco-friendly materials [6]. Beyond policy efforts, research and development have focused on the development of eco-friendly mask filters. The Korea Institute of Chemical Technology developed a biodegradable mask filter using polybutylene succinate (PBS), a biodegradable plastic that can be 100% degraded naturally within a month under composting conditions [7]. The biodegradable mask filter demonstrated increased breathability, moisture resistance, and reusability compared to conventional filters and biodegraded in 28 d in compostable soil conditions in a litter test. Natural polymers, such as cellulose and chitosan, are promising sustainable alternatives for mask materials [8]. Although natural polymers such as cellulose, chitosan, and bamboo fibers are considered promising sustainable alternatives for mask materials due to their biodegradability and eco-friendliness, they possess inherent limitations. Natural polymers often have inferior mechanical strength, limited thermal stability, and lower moisture resistance compared to synthetic polymers. To address these challenges, research into advanced synthetic biodegradable polymers, such as polylactic acid (PLA) and polybutylene succinate (PBS), has become crucial. These materials combine biodegradability with superior mechanical strength, thermal resistance, and processability, enabling the development of products that not only reduce environmental impact but also satisfy stringent safety and usability requirements.

Masks made from polylactic acid (PLA) and bamboo fibers have exhibited effective filtration and biodegradability, with the ability to control degradation rates through starch content [9,10]. PLA is the most researched and used biodegradable polymer [11]. Whereas conventional synthetic polymers are manufactured through distillation and polymerization from non-renewable petroleum reserves, PLA can be derived from renewable resources, such as corn starch or sugarcane [12], and is compostable and recyclable [13].

In addition, current masks have the potential to allow infectious agents, such as viruses and bacteria, to remain on the surface of the mask for extended periods and become a source of secondary infection [14]. Indeed, researchers have detected influenza viruses on the surfaces of N95 and surgical masks [15]. Unlike temporary sterilization treatments, such as disinfectant sprays, antibacterial and antiviral agents can be processed into textile products and plastic moldings, although they require excellent heat resistance. The development of antimicrobial masks has gained attention. Antimicrobial masks are expected to effectively inactivate infectious agents that come into contact with the mask surface, thereby lowering the incidence of secondary infections [16]. In addition to their high filtration efficiencies [17], some biodegradable mask materials, such as bamboo, have exhibited bacterial and mite inhibitory properties, resulting in improved health safety [9].

The COVID-19 pandemic highlighted the importance of standards for masks [18]. The standard for masks for general use in South Korea is the MFDA (Ministry of Food and Drug Safety)'s 'Regulations for the Authorization, Notification, and Examination of Quasi-drugs' (Notification No. 2020-06) [19], which is a sub-notification of the Pharmacy Act. The MFDA regulates the approval, notification, and review of various quasi-drugs, of which masks are a subset. Therefore, it is not exhaustive, and a separate explanatory document (Guidelines for Standardized Standards for Health Masks) is available [20].

The U.S. 'N95 dust mask' is an industrial mask standard for hazardous work environments with high exposure to respiratory illnesses that are different from normal daily life, so it is overkill for masks to protect against the COVID-19 pandemic past fine dust [18]. The Korean government introduced the KF (Korean Filter) mask certification method after

recognizing that the air quality in Korea, such as fine and yellow dust, has a significant impact on health. The KF rating categorizes masks according to the performance of the filter inserted as an interlayer in the mask products. The definition of 'nonwovens for mask filters' includes not only MB but also composite nonwovens that combine MB and spunbond (SB). Masks are provided with a KF rating (KF99, KF94, and KF80). The number indicates the product's performance in terms of the particle blocking rate for harmful particulate substances or infectious agents, such as yellow dust and fine dust. For example, a KF94 mask should be able to block at least 94% of fine particles with an average size of 0.4 μm. The facial leakage rate and respiratory resistance are other key indicators. The facial leakage rate quantifies the degree to which outside air leaks through the gap between the face and mask when wearing a mask, while the facial respiratory resistance is the ability to prevent foreign substances from entering the respiratory tract while still allowing you to breathe [21]. Table 1 specifies the management standards for each grade of domestic health masks and their levels.

Table 1. Domestic health mask stewardship standards.

Rating	Criteria			Usage Examples
	Dust Collection Efficiency	Facial Intake Resistance	Facial Leakage Rate	
KF80	80.0%+ blockage of average particle size 0.6 μm (Sodium chloride test)	6.2 mmH_2O or less or 60 Pa or less	25.0% or less	For sulfur
KF94	>94% of average particle size of 0.4 μm (Sodium chloride and paraffin oil test)	7.2 mmH_2O or less or 70 Pa or less	11.0% or less	For sulfur, For quarantine
KF99	>99% of average particle size 0.4 μm (Sodium chloride and paraffin oil test)	10.3 mmH_2O or less or 100 Pa or less	5.0% or less	

(Source: Food and Drug Administration Guidance on Standards for Face Masks) [22].

The growing demand for SB nonwovens underscores the need to develop nonwovens with biodegradable polymeric materials to mitigate the environmental burden associated with waste. This study aimed to address the environmental pollution problem associated with existing masks by developing a mask certified by the MFDA that meets KF94 and MFAD levels. To achieve this, a water-punching nonwoven material using (PLA) or natural (cotton, bamboo, and Tencel) materials was developed to replace the synthetic lining (mainly PP/PE SB) of the three-layer structure, and a biodegradable MB filter was developed to replace the PP MB filter. In addition, accessories such as earloops and packaging materials were redesigned using sustainable alternatives. This study highlights the potential of sustainable mask production and its role in addressing plastic waste.

2. Materials and Methods

2.1. Overview

We developed the outer layer, filter, and inner layer of the mask by blending PLA fiber, a biodegradable material that can replace synthetic materials in the lining of the KF 94 mask, including cotton fiber and Tencel fiber. The developed nonwoven fabric was post-processed to provide additional antibacterial and deodorizing properties. A prototype KF 94 protective mask certified by the Ministry of Food and Drug Safety was developed

with improved shape stability, ease of breathing, and touch sensation in the lining area. Table 2 presents the design details of the materials and weight for each mask structure (outer layer, filter, and inner layer). The optimized fiber mixing ratio for each type of material was explored considering the biodegradability and physical properties.

Table 2. Material design by mask structure.

Classification		Materials	Manufacturing Method	Weight (g/m^2)
KF 94	Outer layer	PLA/Cotton	Water punching	50
	Interlayer (filter)	PLA MB	Melt blown	30
	Inner layer	Cotton/Tencel	Water punching	40

2.2. Development of Mask Materials

To develop the inner-layer, filter, and outer-layer nonwoven fabrics, the biodegradable PLA fiber was mixed with other materials, such as cotton and Tencel fibers. The fiber lengths of PLA were 38, 25, and 38 mm. The detailed properties of the short PLA fibers, which are the core of the biodegradable material, are listed in Table 3. The inner-layer nonwoven fabric was produced by water punching the web using natural cotton and Tencel to create a nonwoven fabric. To facilitate the production of nonwoven fabrics, natural cellulosic fibers are subjected to a softener treatment process rather than conventional processes. To manufacture the intermediate filter, the raw PLA material was fed through a mixing machine to untangle the tangled raw material and simultaneously mix the raw material at the same time. After adjusting the weight of the web formed using a web drafting machine, the fibers were tangled by water flow discharged at high pressure from a small nozzle through a water-punching machine without using glue to produce an eco-friendly nonwoven fabric. Two types of mask outer-layer nonwoven fabrics and three types of inner-layer nonwoven fabrics were produced by using different material blending ratios. Surface photographs were taken using an optical microscope at 80x magnification.

Table 3. Ingeo PLA short-fiber properties.

Physical Properties	
Insularity (dtex)	1.5
Strength (cN/tex)	32–36
Elongation (%)	50–60
Moisture content (%)	0.4–0.6
Number of crimps ea/10 cm	30–35
Sectional shapes	Circle
Surface Characteristics	Smooth
Density (g/cm$^{3)}$	1.25
Melting point (°C)	170

2.3. Function Processing of Nonwovens

The nonwoven fabric of the inner layer of the mask, which was a 90:10 blend of cotton and Tencel, was processed with natural substances to provide antibacterial and deodorizing properties. Jade was used as the functional material as it has antibacterial and deodorizing properties and can be processed into existing fibers [23]. The antibacterial effect

of jade stems from its emission of far-infrared rays, which can cause protein denaturation in bacteria and inhibit metabolic activity [24]. This constitutes a physical mechanism of antimicrobial action, similar to that of copper and silver.

Jade mineral was selected at a concentration of 3% and the binder at 5%. The embedded natural product was treated and dried in the form of padding after immersion using the immersion method (Tables 4 and 5). The jade was colorless, and the overall penetration of the functional substances was good. Because of the content of cotton material, it exhibited soft-touch characteristics compared to conventional nonwoven materials. After processing, the antibacterial properties (KSK 0693:2003) [25] and odor resistance (gas detection tube method) [26] of the nonwoven material were evaluated.

Table 4. Cotton nonwoven jade experimental process and samples.

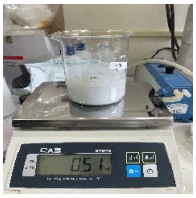
				
Water weighing	Jade weighing	Binder addition and mixing	Immersion	Drying

Table 5. Nonwoven fabric processing conditions and post-processing samples.

Set natural Content (g)			Sample After Machining
Jade	**Water**	**Binders**	
50	180	10	

2.4. Biodegradability Testing

Biodegradability testing of the interlayer filter nonwoven fabric of health masks is a critical factor in assessing the environmental impact of disposable masks. This test evaluates the effectiveness of material degradation under aerobic conditions, which is essential given the growing concern regarding plastic pollution from conventional masks. Biodegradability testing indicates the degradation rate of a material by measuring the CO_2 production in a closed system [27]. A biodegradability test (45 d test) was conducted on the filtered nonwoven material in the middle layer of the three-layer structure of the health mask. Based on ISO 14855 [28], the most widely used biodegradation test method for measuring the aerobic biodegradation and decay of plastic materials under controlled composting conditions (measuring carbon dioxide production), each country has created and operated relevant standards. We referred to the standard of 60% or more degradation of the reference material within six months (ASTM D 5338, USA) [29]. The rate was compared to the standard substance evaluated by the Korea Apparel Testing & Research Institute (KATRI), an accredited testing organization, according to the ISO 14855 [28].

2.5. KF 94 Rating Test

The purity, dust collection efficiency, inhalation resistance, and total inward leakage rate, which are the standard test parameters for evaluating KF 94 grade, were tested. Purity

was tested in accordance with the Standards and Test Methods for Quasi-drugs (KFDA Notification No. 2022-45) [30].

The dust collection efficiency was based on the sodium chloride and paraffin oil test method, which was also tested in accordance with the standards and test methods for quasi-drugs [30] (KFDA Notification No. 2022-45). A 1% sodium chloride solution was prepared by dissolving sodium chloride reagent in water. Then, sodium chloride aerosol was generated using a dust collection efficiency testing device. The facial surface of the sample was placed into the dust collection efficiency testing equipment, and the sodium chloride aerosol was passed through the facial surface at a flow rate of 95 L per min. The aerosol concentration was measured before and after the facial surface passed through the equipment, at 3 min after the test began. The measured value was calculated as the average value obtained from measurements taken over 30 ± 3 s.

The inhalation resistance was tested in accordance with the Guidelines for Reference Standards for Respirators (2021.03) [31]. The face of the test specimen was fitted in the test phantom shown in the figure below so that the mask fit snugly without deformation or air leakage. Then, the differential pressure (Pa) was measured when air was passed through at a continuous flow rate of 30 L per min.

Finally, the total inward leakage rate test was conducted in accordance with the Guidelines for Reference Standards for Respirators (2022.05) [32]. The total inward leakage rate test measures the amount of air leakage when a person wears a mask and performs activities. A 2% sodium chloride solution was prepared by dissolving sodium chloride reagent in distilled water. Then, an aerosol generator was used to produce sodium chloride aerosol. The test subject wore the test sample on their face according to the product's instructions for use and dosage. The concentration of sodium chloride aerosol inside the test mask was measured.

2.6. Bacterial Filtration Efficiency

The bacterial filtration efficiency was measured in accordance with the standards and test methods for quasi-drugs (MFDA Notification No. 2022-45) [31]. The number of bacteria before and after the aerosol passed through the mask during the filtering process was compared to calculate the bacterial filtration efficiency as a percentage.

2.7. Prototype Development

To develop a finished health mask product using biodegradable materials, we measured the components of existing masks and the detailed size of each mask part. The components of the mask included a top plate, middle plate, bottom plate, earloop band, and nose support. The detailed size of the mask measured 10 items, including weight, thickness (middle plate), length (width, length, side, top, and bottom), strap length, width, spacing of the earloop band, and insertion position and size of the nose support (Table 6).

Six samples were used as targets for detailed size measurement items. The shape type was two-stage longitudinal folding, as shown in Table 7. For the two-stage longitudinal folding product, the side, top, and bottom lengths were not measured (items 5, 6, and 7, respectively, in Table 6).

The size measurements of adult mask samples are presented in Table 8. The weight ranged from 4.35 g to 5.12 g for the vertically folded masks, and there was no significant difference in weight by mask type. For thickness, we measured the top, middle, and bottom layers of the vertically folded masks and found that the top and bottom layers had the same thickness, while the middle layer was slightly thicker (by up to 15%). In the case of length, the width varied greatly by product, but the height varied relatively little; therefore,

the average length of the product in the direction of the length of the face could be used as a reference.

Table 6. Detailed sizing metrics by mask area.

Metric			
1	Weight		
2	Thickness		
3	Length (folded in half)	Width	
4		Height	
5	Ear band (elastic)	Length	
6		Width	
7		Between band ends	
8	Position of nose wire	From the top edge	
9		Width	
10		Length	

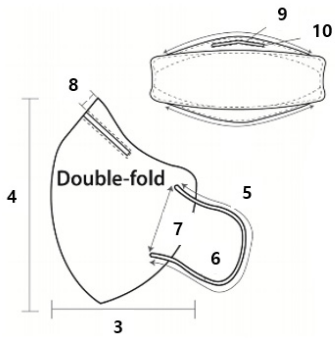


Table 7. Sample health mask (large).

2-Stage Vertical Folding		
1 (Everfresh®)	2 (Flow®)	3 (Exploration®)
		
4 (Polytechnic®)	5 (Safe®)	6 (Line Story®)
		

The earloop bands were primarily made of elastic and stretchable polyurethane nylon fused to both ends of the mask, with some masks allowing the length of the band to be adjusted to fit the shape and size of the wearer's face to improve comfort. The average length of the earloop band was 150.8 mm for the vertical folding masks. The earloop band was the item with the largest variation in length, which is difficult to use as a reference because the elasticity varies depending on the characteristics of the band. The shapes of the earloop bands varied between the two-stage vertical folding masks, with flat bands used for the two-stage vertical folding masks, and smooth and rounded bands used. The nose support of the mask was attached to all sample masks in the form of an insert, and a polyvinyl chloride-covered wire with good moldability was mainly used, which is considered necessary to switch to biodegradable materials in the future.

Table 8. Adult mask sizing results.

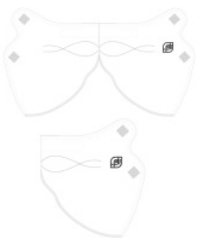
Type	Measurement	① Weight (g)	② Thickness (mm)	Length (mm)	
				③ Width	④ Height
2-level portrait Folding	1	4.22	1.08	22.80	14.80
	2	4.78	0.99	23.50	15.60
	3	4.65	1.05	21.40	16.10
	4	4.49	0.98	21.60	14.30
	5	5.07	1.21	18.20	14.60
	6	5.11	0.89	24.10	15.90
Mean		4.72	1.03	21.93	15.22
S.D		0.342	0.109	2.109	0.747
Z		−1.746	−2.529 *	−2.443 *	−3.013 *

Type	Measurement	Elastic band (mm)			Position of nose wire (mm)		
		⑤ Length	⑥ Width	⑦ Between band ends	⑧ From the top edge	⑨ Width	⑩ Height
2-level portrait Folding	1	16.10	0.40	4.60	0.90	9.30	0.50
	2	15.50	0.40	5.10	1.00	10.70	0.50
	3	14.80	0.30	5.50	1.00	12.10	0.40
	4	13.60	0.30	5.30	0.90	8.90	0.35
	5	16.00	0.50	5.00	0.70	11.60	0.40
	6	14.50	0.30	4.80	0.80	12.30	0.40
Mean		15.08	0.37	5.05	0.88	10.82	0.43
S.D		0.882	0.075	0.327	0.107	1.320	0.056
Z		−1.651	−1.658	−2.228 *	−2.443 *	−1.747	−2.888 *

* $p < 0.05$.

Four surface designs were developed (Table 9), and the final prototype was constructed using an average of six samples (Figure 1). According to the 'Guidelines for Standards for Droplet-Blocking Masks' presented by the MFDS of South Korea, masks with a vertical length of 150 to 170 mm are classified as large. As the average value for our mask fell within this range, it can be classified as a large mask.

Table 9. Prototype design.

Development Design			
			
			

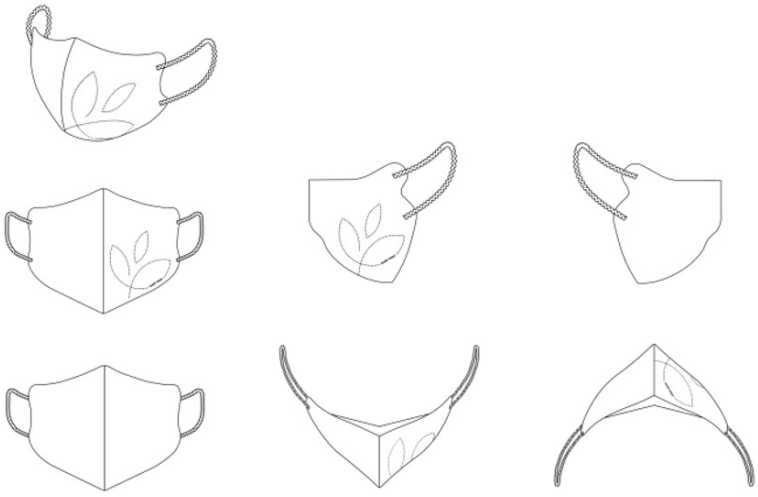


Figure 1. Design drawings (front, side, and back) of the final development prototype.

2.8. Prototype Wearability Evaluation

Ten healthy adult women in their 30s were selected to evaluate the prototype wearability. The purpose and method of the experiment were explained to them before the experiment, and their consent was obtained. The head and facial measurements of the participants are presented in Table 10.

Table 10. Size Specifications for 10 subjects.

Item	Subjects	Average Size for a Woman in Her 30s
	Mean (S.D.)	Mean (S.D.)
Head circumference	54.5 (1.3)	55.4 (1.6)
Head height	19.1 (1.8)	22.4 (1.0)
Head width	15.3 (0.2)	16.0 (0.6)
Nose width	3.5 (0.1)	3.1 (0.3)
Nose height	1.6 (0.1)	1.3 (0.2)

The evaluation was conducted using one existing product, two sample products, and one developed product based on products of similar weights, as shown in Table 11.

Table 11. Mask types and characteristics for wearability assessment.

Item	Categorization	Weight (g)	Thickness (mm)	Inhalation Resistance (Pa)	Total Inward Leakage (%)	Size	Layer
M0	Commercial product	4.60	1.08	8.8	9	L	4
M1	Development (raw)	4.70	1.11	6.7	9	L	3
M2	Development (Jade)	4.70	1.12	7.0	9	L	3

To determine changes over time, assessments were conducted 15 and 30 min after the subjects donned the masks. In order to compare the wearing evaluations of six types of masks with relatively short evaluation intervals, it was determined that it would be

meaningful to conduct the evaluations simultaneously, even if the time intervals were relatively short. In addition, the minimum wearing time was designed to minimize fatigue for the wearers. A standard environment (27.0 ± 0.1 °C, 50.0 ± 10.0% RH, 0.1 m/sec) was maintained to ensure that subjects were comfortable while wearing the mask. The evaluated parameters were warmth, wetness, comfort, stuffiness, and hygiene, all of which were rated by the participants on a 7-point scale. The data of the subjective comfort evaluation were analyzed using SPSS 24.0 to obtain the mean and standard deviation of each evaluation item. Analysis of variance (ANOVA) and post hoc (Duncan's) tests were performed for comparative analysis between the experimental masks.

3. Results

3.1. Nonwoven Production for Biodegradable Material Applications

The surface photographs taken using SEM (JSM-7800F Prime, JEOL Ltd., Tokyo, Japan) are shown in Table 12. It shows images presented to analyze the overall material arrangement and breathability through pores in the nonwoven fabric layers that make up the mask. By comparing the 150× magnification photos in Table 12, it can be seen that the nonwoven fabrics were made uniformly using the water-punching method, even when the PLA material was increased to 20%, compared to the nonwoven fabrics with 10% PLA material. The micrographs of the surface of the material in Table 12 show that the porosity of the surface increased slightly as the percentage of Tencel increased from 10% and 30% to 50%. The inner layer is formed by varying the content of Tencel in cotton fiber. Even when the content of Tencel, which has fine fibers, is increased, the nonwoven fabric is well formed, and fine pores can be observed. This is likely owing to the different fiber fineness of the materials used [33].

Table 12. Photograph of the surface of the developed nonwoven fabric (x150).

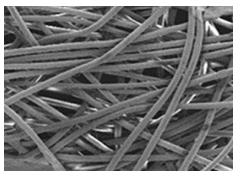
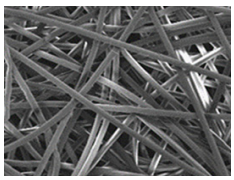
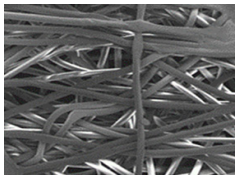
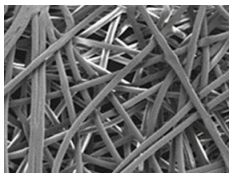
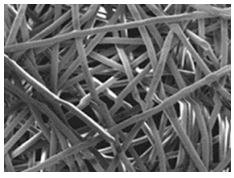
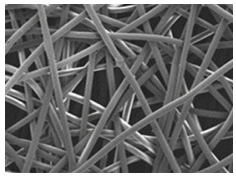
NO.	Purpose	Mixing Rate	X150
1	Outer layer	Cotton + PLA (90:10)	
2		Cotton + PLA (80:20)	
3	Filter	PLA 100	

Table 12. *Cont.*

NO.	Purpose	Mixing Rate	X150
4	Inner layer	Cotton + Tencel (90:10)	
5		Cotton + Tencel (70:30)	
6		Cotton + Tencel (50:50)	

3.2. Antibacterial Properties and Odor Resistance of Nonwovens

The antibacterial properties (KSK 0693:2003) [23] and odor resistance (gas detection tube method) [26] of the nonwoven material were evaluated. The antibacterial property was 99.8%, and odor resistance was 80%. Deodorization is considered excellent if it exceeds 80%; therefore, it was confirmed that the developed nonwoven material could provide excellent antibacterial and deodorization properties after jade processing.

3.3. Functional Evaluation

The biodegradation rate in the 6-month biodegradability test was 70.1%, which exceeded the standard of 60% for biodegradability according to ASTM D 5338.

The purity, dust collection efficiency, facial inhalation resistance, and leakage rate, which are the standard test parameters for evaluating KF 94 grade, were tested. The color was not darker than that of the potassium chromate comparison solution; therefore, it was judged to be suitable. The dust collection efficiency after treatment was more than 94% and was, thus, judged to be suitable. The inhalation resistance was measured to be 70 Pa or less and was, thus, considered acceptable. In the total inward leakage rate test, more than 46 out of 50 leakage rate test values were below the reference value in five exercises of 10 test subjects, which is 11% or less of the total. Therefore, the product was deemed acceptable. The bacterial filtration efficiency was measured as 95% or more and judged to be suitable. Table 13 shows a comparison table of the functionality of existing KF-rated masks and the developed masks. The developed biodegradable mask maintains the same KF94 filtration performance while significantly improving biodegradability, antibacterial properties, comfort, and environmental sustainability. It outperforms conventional KF-rated masks across key aspects such as inhalation resistance and surface softness.

Table 13. Photograph of the surface of the developed nonwoven fabric.

Category	Conventional KF-Rated Mask (PP/PE-Based)	Developed Biodegradable Mask (PLA/Natural Fiber-Based)	Superior Performance
Material Type	Polypropylene (PP), Polyethylene (PE)	PLA fiber, Cotton, Tencel (natural fiber blend)	Developed Mask
Biodegradability	Very low (takes over 450 years to degrade)	Over 70% biodegradation (decomposes within 45 days in compost)	Developed Mask
Antibacterial Properties	None or only temporary sterilization	Long-lasting antibacterial properties through jade coating (over 99.8%)	Developed Mask
Odor Resistance	None or limited	Excellent (over 80% deodorization rate)	Developed Mask
Surface Comfort (Softness)	Slightly rough	Softer touch (cotton + Tencel blending)	Developed Mask
Environmental Impact	Significant carbon and toxic gas emissions from landfilling or incineration	Reduced carbon emissions and landfill burden via biodegradable materials	Developed Mask
Filtration Efficiency (KF94)	≥94%	≥94%	Equivalent

3.4. Prototype Evaluaion

The results of the subjective fit evaluation of the experimental masks by wearing time are presented in Table 14.

For wetness, the commercial product (M0) scored 4.4 points, while the developed products (M1–M2) scored 2.2–2.4 points ($p < 0.01$). Thus, the developed products felt less wet than existing products, indicating that the wetness of the mask lining was significantly reduced when worn for a long time. However, there was no significant difference between the developed product and the commercial product in comfort. Comfort is a comprehensive sensory value and was evaluated by increasing the experimental time to 15 and 30 min. Given that these are not long durations, it was difficult to determine differences in comfort. For stuffiness, M0 scored 4.2, while the developed products (M1–M2) scored 2.8–2.9 ($p < 0.01$), indicating that the developed product felt less stuffy than the existing product. The product was developed with three layers, whereas the existing product had four layers. In addition, the use of nonwoven material reduced the inhalation resistance in the developed product. Table 11 confirms that the inhalation resistance of the developed product was low.

For hygiene, it was expected that the lining material developed in this project would have a significant impact on the deodorization rate. According to the results, the commercial product's hygiene rating was low, at 3.4, while both developed products had excellent scores (M1: 6.1, M2: 6.3).

In the subjective fit evaluation of the three experimental masks, the performance of the developed product outperformed the commercial mask in four categories after 30 min of wear, particularly stuffiness and hygiene. In the case of stuffiness, it is judged that the outer part of the mask was tightly fitted, but the nose, cheeks, lips, and chin were not tightly fitted, providing comfort during mouth movements and making it easier to breathe. The excellent hygiene judgement likely stems from the excellent deodorization of the developed functional processing material. A previous study [34] emphasized the importance of facial adhesion when developing masks for protective purposes. As can be seen from the total inward leakage values in Table 11, the leakage rates were identical, indicating that they did not affect the performance of the mask products.

Table 14. Subjective fit evaluation results (N = 10).

Item		M0	M1	M2	X^2
		Mean (S.D.)	Mean (S.D.)	Mean (S.D.)	
Wear for 15 min	Thermal sensation	5.0 (1.2)	4.4 (1.8)	4.4 (0.8)	1.462
	Wetness	3.0 (1.7)	4.4 (1.8)	4.4 (0.7)	1.152
	Comfort	4.8 (1.0)	4.6 (1.6)	4.6 (1.5)	1.956
	Frustration	4.8 (1.6)	4.8 (1.7)	5.0 (1.2)	2.812
	Hygiene	3.8 (1.1)	4.0 (1.3)	4.1 (1.3)	1.887
Wear for 30 min	Thermal sensation	5.4 (1.3)	3.2 (0.9)	3.4 (1.1)	5.438 **
	Wetness	4.4 (1.6)	2.2 (1.1)	2.4 (0.8)	4.371 *
	Comfort	4.8 (1.3)	5.6 (0.8)	5.3 (0.6)	1.294
	Frustration	4.2 (1.2)	2.8 (0.6)	2.7 (0.8)	4.459 *
	Hygiene	3.4 (0.8)	6.1 (0.4)	6.3 (0.5)	5.792 **

Note: M0 commercial product, M1,2 developed product. * $p < 0.05$, ** $p < 0.01$.

The results of this study are significant in that they showed that, in addition to adhesion, it is important to devise a material composition and product design form that enables comfortable and pleasant breathing.

4. Discussion

We investigated the development of masks using biodegradable and eco-friendly materials to solve the environmental problems associated with KF-grade health masks. We designed the main components of the mask (inner layer, outer layer, and filter) by applying PLA-based biodegradable fibers and natural materials and conducted functional processing using jade to enhance the antibacterial and deodorizing properties. While meeting the performance criteria of the KF 94 grade (dust collection efficiency, facial leakage rate, inspiratory resistance, etc.), the biodegradability of the material exceeded 70%, proving that it can reduce environmental pollution after disposal.

The most notable advancement in this study is the integrated approach to create a fully biodegradable mask design by replacing the outer, filter, and inner layers of the mask with biodegradable materials. This contrasts with previous studies that focused mainly on replacing the filter layer. This integrated approach significantly reduces the environmental impact of discarded masks. In addition, a coating technology using a natural mineral, jade, was introduced to provide antibacterial and deodorizing properties. Unlike conventional antibacterial materials, this approach maximizes the use of natural materials that are safe for the human body. In addition, oak-based coatings have low potential for releasing harmful substances and maintain their effectiveness even after long-term use, making them more sustainable than conventional antibacterial masks.

The comfort of the developed product was improved compared to an existing product, especially in terms of stuffiness and improved hygiene. The lightweight and highly elastic earloop bands and lower respiratory resistance showed potential to reduce fatigue during prolonged wear. However, the low sample size (10) in the wearability test limits the generalizability of the research results as they cannot adequately represent the varied characteristics of the mask-wearing population, including age, gender, face shape, and skin sensitivity. Therefore, it cannot be concluded that the effects observed in the subjective evaluation apply to the entire population. In addition, results based on a small number of

subjects may be greatly influenced by individual differences and subjective evaluations, limiting their reliability and reproducibility. Therefore, future studies need to conduct expanded wearability evaluations targeting larger and more diverse populations.

Disposable face masks have become a staple of modern life. However, there are no official guidelines for recycling, and reports of improper disposal are increasing. Eventually, used masks are classified as contaminated waste and incinerated, causing serious environmental pollution problems owing to the emission of toxic substances such as formaldehyde and carbon dioxide [3]. Regulatory and certification guidelines should be established to promote the development and distribution of eco-friendly masks.

Switching to biodegradable materials will help address the ecological challenges posed by synthetic masks that contribute significantly to waste.

Biodegradable masks mainly utilize materials such as PBS. However, this study presented a new approach by selecting PLA fibers as the main material. PLA is a biodegradable polymer made by polymerizing lactic acid extracted from plant-based raw materials, such as corn and sugar cane. It has the advantages of superior mechanical strength and excellent processability compared to PBS. Therefore, the design maintains the structural stability of the mask while effectively managing the decomposition period.

Biodegradable masks reduce the proportion of waste sent to landfills and minimize greenhouse gas emissions during decomposition. From this perspective, this study shows the potential for sustainable development through the development and commercialization of eco-friendly health masks and will serve as an important reference for further research and policy formulation. However, in this study, although biodegradable materials were applied to the mask body, non-biodegradable materials were still used in the nose support and earloops and as packaging materials; therefore, further research is needed to commercialize biodegradable materials to maximize the overall eco-friendliness of masks. In addition, our study was based on KF 94 standards; therefore, comparative studies and compatibility research with international certification standards such as N95 and FFP2 are necessary for global market entry.

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Abbreviations

The following abbreviations are used in this manuscript:

MB	Melt-blown
MFDA	Ministry of Food and Drug Safety
SB	Spunbond
KF	Korean filter

PP	Polypropylene
PLA	Polylactic acid
PBS	Polybutylene succinate

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