Asia-Pacific Journal of Science and Technology: Volume: 27. Issue: 02. Article ID.: APST-27-02-11. Research Article

Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by the Research and Graduate Studies,
Khon Kaen University, Thailand

Life cycle assessment and performance of mask pad coated with lignin from empty fruit bunches

Kittitat Sirivechphongkul[1], Penjit Srinophakun[1,2,*], Jackapon Sunthornvarabhas[3], Anusith Thanapimmetha[1,2], Hui-Min D. Wang[4], Maythee Saisriyoot[1,2] and Nutchapon Chiarasumran[1,2]

[1]Sustainable Energy and Resource Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand
[2]Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand
[3]MITR PHOL Group, Phu Khiao, Chaiyaphum, Thailand
[4]Graduate Institute of Biomedical Engineering, National Chung Hsing University, Taichung City, Taiwan
[*]Corresponding author: fengpjs@ku.ac.th

Received 9 July 2021
Revised 21 September 2021
Accepted 5 October 2021

Abstract

Life cycle assessment (LCA) was used to investigate a mask pad made from muslin and salo fabric. First, the antimicrobial properties and antimicrobial performance of the mask pad were determined. Then, the mask pad was coated with lignin extracted from an empty fruit bunch (EFB). H_2SO_4-pretreated EFB had a higher lignin composition (42.78%) than unpretreated bunches (12.84%). Then, pretreated EFB was subjected to delignification using NaOH; 69.57% lignin purity was obtained. For some conditions, chitosan was used as a binder to produce a better coating. The minimum inhibitory and minimum bactericidal concentrations of EFB lignin against *Staphylococcus aureus* were 6,400 and 12,800 µg/mL, respectively. Various lignin concentrations and mixtures of lignin and chitosan were coated on muslin and salo fabrics. Adding lignin (0.125% w/v) and chitosan (0.25% w/v) to both fabrics produced the highest possible score of 5 in the colorfastness test and were studied further. The coated fabric could reduce the growth of *S. aureus* by 30-48% over 24 h, based on the AATCC100-2012 standard. The LCA results showed that the lignin-coated textile masks had the highest environmental impact in the midpoint category on marine and freshwater ecotoxicity (0.955 and 1.2 kg 1,4- dichlorobenzeen (DCB), respectively) and in the endpoint category on human health and ecosystem. Most impacts were from electricity and water consumption in the coating solution process and in producing the lining for the textile masks. Furthermore, the production of the textile mask pads was cost-effective and less expensive compared to the other types of mask studied.

Keywords: Lignin, Life Cycle Assessment, Antimicrobial activity, Facemask

1. Introduction

Antimicrobial textile products are of the utmost importance to medical devices because they can prevent human contact with certain types of bacteria, particles, and viruses through the respiratory system and in a healthcare environment and can be used in conjunction with physical distancing and hand hygiene. The textile known as Muslin is used in fabric because of its strong fibers, resulting in tiny pores suitable for mask production. For example, a face mask may include three layers consisting of two protective layers that sandwich a middle bacterial lining layer. Thus, an antimicrobial coating on the fabric surface is the most straightforward improvement of a medical device (such as a face mask or textile) [1].

Empty fruit bunches (EFB) from the palm oil industry are one form of residue that amounts to about 1 million t per year. The main components of EFB are cellulose, hemicellulose, and lignin. Cellulose and hemicellulose can be used to produce bioethanol, while the lignin is removed and discarded. The current research investigated value-added lignin as a natural and biodegradable raw material for human applications.

Lignin is a compound of carbon, hydrogen, and oxygen combined into several subunits, resulting in a complex with a high molecular weight. It has natural hydrophobicity and is dark brown when treated with acid or alkali. Lignin is a phenolic polymer formed from monolignils (monomers): p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol. The phenolic compounds (hydroxyl and methoxyl groups) in lignin are biologically active, having antioxidant and antimicrobial activity [2,3]. Furthermore, the antimicrobial property of lignin depends on the type of plant from which the lignin has been sourced [4].

An antimicrobial textile mask can be developed by applying a lignin coating on the pad lining the mask. However, lignin cannot be coated on the textile because both the lignin and textile have the same electrostatic charge type (anion); thus, a binding agent is necessary. Chitosan is a good candidate as a binding agent because it has cations on its surface and is biodegradable. Many techniques are used in coating, including layer-by-layer deposition and mixed solution coating. However, a simple method is soaking, where the principle is the diffusion and absorption of the coating solution in the lining material [5].

Due to the current transmission of COVID-19, the disease caused by a new coronavirus called SARS-CoV-2, there is an ongoing worldwide demand for surgical masks, to control or slow down the spread of the infection and disease. However, surgical masks that have been used for a while still harbor surviving microorganisms on the mask surface, limiting the safe and effective use of the mask due to the accumulation of germs on any part of the wearer's body that comes in contact with the mask. These issues have led to the development of face masks with inherent antimicrobial properties from a coating on the mask. Hygiene standards require a medical-surgical mask to be used only once a day. Thus, there is demand for a washable textile mask made from cotton, for example, that is reusable and can be produced locally, conveniently, and sustainably and that is environment-friendly. However, such textile masks are still under development to determine the efficacy of parameters such as breathability, water droplet resistance, air permeability, and additional developed property, namely, that the mask is antimicrobial.

The efficacy of a textile mask could be increased by adding a lining layer to filter bacteria and small particles and enhance the mask's antimicrobial properties. The antimicrobial property of lignin makes it a candidate for coating on a mask. The present work investigated the antimicrobial activities of an EFB lignin coating on a textile mask using chitosan binding and evaluated other properties: the durability of lignin adhesion on the surface, water-resistance properties, and chemical bonding properties. In addition, a thorough environmental impact assessment throughout the manufacturing process was undertaken of the use of textile masks with lignin and chitosan-coated linings. The process considered a "cradle-to-the-grave" assessment regarding climate change and cumulative energy demand. Finally, life cycle assessment (LCA) was evaluated based on the production steps in the lignin extraction process and the whole life cycle of the textile mask with a coated lining pad and comparisons were made with the use of other masks (a disposable surgical mask and an N95 respirator mask) as well as cost-estimation analysis of the masks.

2. Materials and methods

2.1 Materials

The EFB was kindly provided by the Suksomboon Group (Chonburi province, Thailand). The EFB was boiled and sun-dried at 65℃ for 2 days and then crushed. Then, the EFB was cut into pieces of 0.25-0.42 mm on average that were dried in an oven at 105℃ for 3 h or until the weight was constant (AOAC 1999) [6]. After that, the EFB composition was analyzed according to the method of Goering and Van [7]. Chitosan (viscosity of 200-800 cP) was purchased from Sigma Aldrich, Germany. Commercial alkaline lignin was purchased from Tokyo Chemical Industry Co., Japan. Sodium hydroxide was purchased from Kemaus, Australia. Glacial acetic acid and sulfuric acid were obtained from QRec, New Zealand. Samples of 100% cotton fabric (Muslin and Salo) were procured from a local textile mill. All chemicals used were analytical grade. The textile mask was obtained from Parada, Thailand. The surgical mask and N95 respiratory were obtained from 3M, Thailand.

2.2 Pretreatment and delignification

The EFB (EFB-to-H_2SO_4 ratio of 1:10 w/v) was pretreated with acid hydrolysis to remove hemicellulose and some cellulose by heating in an autoclave using 8% w/v H_2SO_4 solution at 121℃ for 60 min [8]. Then, the EFB was delignified in 2.5% w/v NaOH solution (EFB-to-NaOH ratio of 1:10 w/v) at 121℃ for 60 min. The mixture was filtered to remove fiber residue and the black liquor was collected for the precipitation step, with the lignin separated using two-step precipitation with 50% v/v H_2SO_4. In the first step, H_2SO_4 was gradually added to adjust the black liquor from alkaline (pH 13) to neutral (pH 7). Then, the black liquor was left at room temperature for 4 h to remove silica sludge and other impurities by precipitation. Next, the solid was removed, H_2SO_4 was added to the solution until it reached pH 2 before being kept at room temperature for 8 h. Finally, the residue was washed with distilled water and dried in the oven at 60°C. The EFB pretreatment and delignification followed the method detailed by Kingkaew [9]. The amounts were determined for acid-soluble lignin and acid-insoluble lignin [10].

2.3 Coating solution preparation

Muslin and Salo cotton textiles were used in this experiment. Lignin powder was dissolved in NaOH at different lignin concentrations of 0.125 and 0.25% w/v. Chitosan (CS) was dissolved in CH_3COOH at different concentrations of 0.25 and 0.5% w/v. Two different coating methods were applied : electrostatic layer-by-layer deposition and soaking in mixed solution. Electrostatic layer-by-layer deposition involved soaking chitosan for 15 min in lignin solution, followed by quick soaking in water to remove the excess lignin, and then drying at room temperature. Subsequently, the respective textile lining was soaked in the chitosan solution for 15 min, quickly soaked in water, and then dried [11].

On the other hand, soaking in mixed solution involved first mixing the lignin and chitosan solution at 50:50 v/v [1]; then the textiles were soaked for 15 min in the mixed solution, quickly soaked in water, removed and allowed to dry. The textile linings were kept in zip-lock plastic bags.

2.4 Colorfastness for durability test

The durability test of the coating solution on the textile mask lining was based on the testing standard ISO 105-E01: 1994 [12]. Figure 1 shows the grayscale color change levels of 1-5. The mask lining was first incubated in deionized water at room temperature under compression (12.5 kPa). Then, the samples were placed in a hot-air oven at 37°C for 4 h and dried at room temperature. The test for a color change compared the grayscale colors of dry mask lining samples before and after compression. Level 5 was the most colorfast, implying no observable change after the durability test [12].

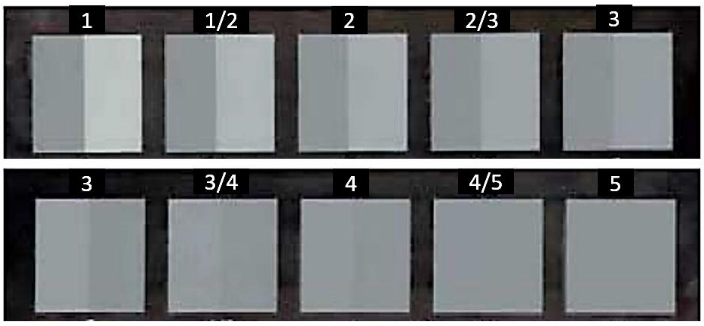


Figure 1 Grayscale of color change. Level 5-4, least color change (best/good); level 3, medium color change (medium); level 2-1; most color change (poor/worst).

2.5 Morphology of textile coated with lignin and chitosan

The physical morphology of the lignin and chitosan-coated textile was investigated using scanning electron microscopy (SEM; JEOL, JSM7001F, USA) with an acceleration voltage of 2 kV and resolution of 100 µm, under nitrogen atmosphere. The samples were dried and coated with gold before analysis. The image zoom was analyzed at 250× magnification to study the arrangement of textile fibers before and after coating.

2.6 Antimicrobial activities

The antimicrobial activities of the lignin extracted were evaluated using Broth dilution testing against a Gram-positive bacterium (*Staphylococcus aureus*). The results were shown as the minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC).

The antimicrobial activities of the lignin and chitosan coating on the mask lining were studied using a standard, quantitative, textile antibacterial method of AATCC 100-2012 against *S. aureus*. The percentage reduction of bacterial growth in the test sample was compared with the control over 24 h (% reduction). The formula for the % reduction from the bacterial count was:

$$\% \text{ Reduction} = \frac{A - B}{A} \times 100\%$$

where A and B are the numbers of colonies determined from the textile mask lining without the coating solution (control) and with coating solution, respectively.

2.7 Air permeability

The pressure drop of the coated mask lining was measured according to the Thai Industrial Standard TISI 2424-2019, using a test area of 190 cm^2 and a testing pressure of 100 Pa, comparable with breathing in/out resistance through a respirator such as a mask. The coated fabric was placed secured across a hollow tube attached with a pressure gauge. Airflow was supplied through one end of the tube and the gauge monitored the pressure change of the air that had passed though the coated fabric sample [13].

2.8 Water contact angle measurement

Contact angles were analyzed by dropping 5 µL of water on the sample surface and measured using a Dataphysics OCA40 . This analysis was measured at room temperature to identify the hydrophobicity of the coated textile, which is one of the properties of a face mask to repel aerosol sprays [14].

2.9 Fourier transform infrared spectroscopy

The chemical characteristic and chemical interaction between the coating solution (lignin and chitosan) on the textile were characterized using Fourier-transform infrared spectroscopy (FTIR; PerkinElmer Inc., USA), with the lignin and chitosan powder analyzed for functional groups using attenuated total reflection FTIR instrument (ATR-FTIR; BRUKER., Alpha-E) at room temperature in the range 350-4000 cm^{-1} with the absorbance measurement determined using a detector with a resolution of 4 cm^{-1} and 16 scans for each average sample [15].

2.10 Life cycle assessment

The textile masks with different coated lining pads were assessed for their environmental impact throughout the product life cycle. The evaluation began by determining the raw material input and output and energy consumption per functional unit using the Simapro Software. Then, the Life Cycle Impact Assessment procedure based on the Ecoinvent database was applied to assess the environmental impact based on ReCiPe 2016 Midpoint/Endpoint (H) V1.04 / World (2010). The life cycle of a textile mask with a lining-coated pad consisted of: lignin extraction (EFB for coating solution preparation), coating procedure, mask and mask lining production, transportation, mask usage, and the mask and mask lining disposal and waste treatment.

2.11 Goal and scope definition

The functional unit was use of a textile mask by a person for 1 year of the COVID-19 pandemic. Therefore, the assumed number of facemasks used annually was 4 masks/year of textile mask and 1 piece/day of lining pad [16].

The system boundaries of the textile masks with a coated lining pad considered from the cradle-to-the-grave in the LCA study were: raw material extraction (coating solution, textile, polymer, additive in the mask), mask production (mask manufacturing process), packaging, transportation (distribution and final use), use phase (maintenance of machine-washing the textile mask), and end-of-life (disposal-incineration).

Table 1 Life cycle inventory (LCI) of the textile mask [16,17].

	Component	Material	Processing	Weight (g)	Energy
Textile* Mask	Inner/outer	Woven cotton (Muslin)	Bleaching textile	6.00	0.01512 kWh/ pieces
	Elastic band	Polyurethane foam	Section bar extrusion	0.25	
Lining*	Lining	Woven cotton (Muslin)	Bleaching textile	1.25	0.002975 kWh/ pieces
		Coating solution	-	0.10	
Packaging	Packaging of textile mask	LDPE wrap (1 piece/wrap)	Blow moulding	3.35	-
	Packaging of lining	- LDPE wrap (50 pieces/wrap)	Blow moulding	3.35	-
		- Cardboard box (50 pieces/box)	-	53.5	-

Note: LDPE: Low-Density Polyethylene. * Weigh, cut out the mask pieces and weigh each separately.

2.12 Life cycle inventory (LCI)

The inventory data included all production phases (lignin coating solution and making parts of the masks) to the disposal phase. The mask was disassembled to obtain an accurate weight of each component (Table 1). Based on usage for 1 year of the textile masks with coated lining pad, in total there were 365 pieces of textile mask lining. One piece of the textile mask could be reused for 3 months by washing every day at 60℃ [18]. Textile mask transportation (distribution and final use) with a coated lining pad was based on 500 km by diesel single-use truck and disposal by incineration.

2.13 Cost estimation of face mask

Costing was investigated of the lignin extraction from EFB and of the coatings of lignin and chitosan on the textile mask lining. The cost estimation consisted of material, operational, and utility costs [19]. The costs for the three mask types were calculated, and their LCIs were analyzed (Table 2), with the textile mask being divided into two parts (the textile mask itself and the coated mask lining). The cost of the textile mask with coated lining pad was compared with a disposable one-time surgical mask and an N95 respiratory mask.

Table 2 Life cycle inventory of use phase to disposal phase [18,20].

Condition	Disposable surgical mask	Textile mask		N95 respiratory
		Textile mask	Coated mask lining	
Wearing	1 piece/day (365 pieces)	4 piece/year (365 days)	1 piece/day (365 pieces)	5 days/piece
Usage	One-time use	Everyday washing (60ºC machine washing)	One-time use	30 min UV-C
Cost (USD)	USD 0.08/piece	USD 0.725/piece	USD 1.47/m^2	USD 1.9/piece

Note: The cost of disposable surgical mask, textile mask, and N95 respiratory are from an online shopping store (Alibaba, Shopee, Amazon)

3. Results and discussions

3.1 Effect of initial lignin content

The compositional analyses of raw EFB, pretreated EFB, extracted lignin, and commercial lignin are listed in Table 3. The pretreated EFB was obtained after acid hydrolysis, and the extracted lignin was obtained after delignification. As shown in Table 3, the amounts of cellulose and hemicellulose (60.08 and 21.20%, respectively) reduced substantially after pretreatment (48.46 and 1.097%, respectively). In contrast, lignin increased from 12.84 to 42.79% due to the acid hydrolysis, because the acid breaks the ether bond between lignin and hemicellulose [21]. Consequently, the acid could digest the hemicellulose into smaller molecules but not the lignin, and thus, the % lignin increased.

Table 3 shows the composition of extracted lignin from this study compared to commercial lignin. An alkali would disrupt the EFB structure. Therefore, the amount of dissolved material in alkaline solution increased [2,22]. Consequently, the acid-insoluble lignin (68.50%) in the extracted lignin was much higher than in the commercial lignin (47.08%). However, the lignin composition may vary depending on the natural features of different biomass sources [23].

Nevertheless, the lignin from the extract was high (122.33 g/kg of Pretreated EFB). However, the actual lignin content that only 84.6 g/kg of Pretreated EFB (total ASL+AIL lignin content 69.16%) could be extracted from the 42.79% lignin content in the pretreated EFB, with 122.33 g of lignin extracted from 1 kg of EFB. Therefore, increasing the extraction yields would improve the delignification process in the future.

Table 3 Composition of raw EFB, pretreated EFB, extracted lignin, and commercial lignin.

Composition	EFB / lignin		
	Raw EFB	Pretreated EFB / EFB lignin	Commercial lignin
EFB composition (%)			
Cellulose	60.084 ± 0.98	48.46 ± 1.87	-
Hemicellulose	21.20 ± 1.42	1.097 ± 0.41	-
Lignin	12.84 ± 0.41	42.79 ± 1.28	-
Ash	0.59 ± 0.15	0.65 ± 0.18	-
Others	5.29 ± 0.46	6.99 ± 0.15	-
Lignin content			
Acid soluble lignin (ASL) (wt%)	-	0.66 ± 0.01	0.53 ± 0.03
Acid insoluble lignin (AIL) (wt%)	-	68.50 ± 1.78	47.09 ± 2.56
Total ASL+AIL (wt%)	-	69.16 ± 1.78	47.62 ± 2.50
Lignin extracts (g/kg of pretreated EFB)	-	122.33 ± 3.98	-
Actual lignin content from extracts (g/kg of pretreated EFB)	-	84.60 ± 2.75	-

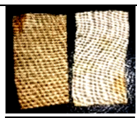
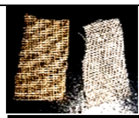
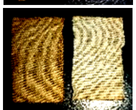
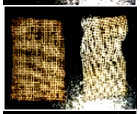
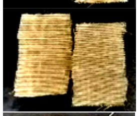
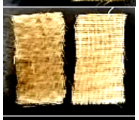
Note: EFB: Empty Fruit Bunches

3.2 Effect of durability and surface morphology of coated textile mask lining

The results from testing colorfastness in water of the lignin-coated (EFBL) and the lignin and chitosan-coated (EFBL & CS) textile mask lining samples are shown in Table 4. Referring to Figure 1, the colorfastness effect of the lignin coating on muslin and Salo had an average level of 2-3 (poor to medium colorfastness). Lignin, as an anion, has the same electrostatic charge as the textile resulting in its low level of colorfastness. Having a binding agent between lignin and textiles would improve the colorfastness. Therefore, the colorfastness in water was high (good to excellent) for Muslin (level 4-5) and Salo (level 4/5 to 5).

The methods of electrostatic layer-by-layer deposition coating and soaking in the mixed solution were compared. It was found that the electrostatic layer-by-layer deposition coating (coating lignin on the first layer and chitosan on the top layer) produced the highest average level 5 (excellent colorfastness) for most tested concentrations. Similar results were found in the mixed solution coating of EFBL 0.125:CS 0.25% w/v conditions, with the Muslin and Salo fabric samples having the highest value of colorfastness in water (level 5).

Table 4 Colorfastness in water of various coated textile mask lining based on ISO 105-E01: 1994.

Condition	Muslin fabric		Salo fabric	
	Sample (before - after)	Color change (Grayscale)	Sample (before -after)	Color change (Grayscale)
EFBL 0.125% w/v		2/3		2/3
EFBL 0.25% w/v		3		3/4
EFBL 0.125%: CS 0.25% w/v (mixed)		5		5
EFBL 0.25%: CS 0.25% w/v (mixed)		4/5		5
EFBL 0.125%: CS 0.5% w/v (mixed)		4		4/5
EFBL 0.25%: CS 0.5% w/v (mixed)		4/5		5
EFBL 0.125%: CS 0.25% w/v (layer-layer)		5		5
EFBL 0.25%: CS 0.25% w/v (layer-layer)		4/5		5
EFBL 0.125%: CS 0.5% w/v (layer-layer)		4/5		5
EFBL 0.25%: CS 0.5 %w/v (layer-layer)		5		5

Note: Textile images before (left) and after (right) durability testing; (mixed) = coated by soaking in a mixed solution of lignin and chitosan; and (layer-layer) = coated using electrostatic layer-by-layer deposition method.
EFBL = Empty Fruit Bunches Lignin CS = Chitosan.

Figure 2 shows images of samples of the coated textile mask lining. The Muslin fabric (Figure 2A) was generally more tightly woven than the Salo (Figure 2D). As a result, there were color changes in both fabrics after coating. In addition, looser fibers due to fiber loss were apparent in the Salo fabric after coating (Figures 2E and 2F); however, this was not evident in the Muslin fabric after coating.

The surface morphology of the lignin and chitosan-coated mask lining was examined using FE-SEM analysis at a magnification of 100 μm (Figure 3). Figures 3a and 3d reveal the flattened and broader fibers of the Muslin fabric compared to the Salo fabric. After coating, a thin film over the fiber gap is visible in Figures 3B, 3C, 3E, and 3F. This thin film helped air permeability during respiration and the mask's small particle filtration efficiency [1,24]. Finally, only the Muslin fabric-coated mask lining was selected.

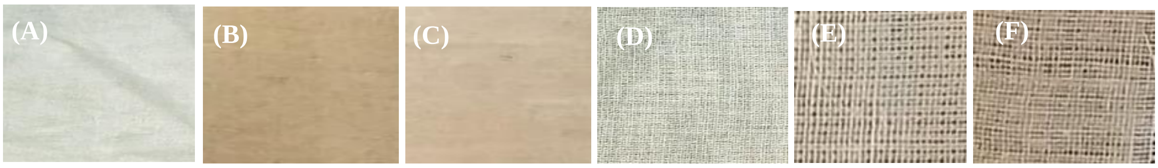


Figure 2 Muslin fabric (A), Muslin fabric coated with EFBL 0.125% w/v (B), Muslin fabric coated with EFBL 0.125:CS 0.25% w/v (C), Salo fabric (D), Salo fabric coated with EFBL 0.125% w/v (E), and Salo fabric coated with EFBL 0.125:CS 0.25% w/v (F).

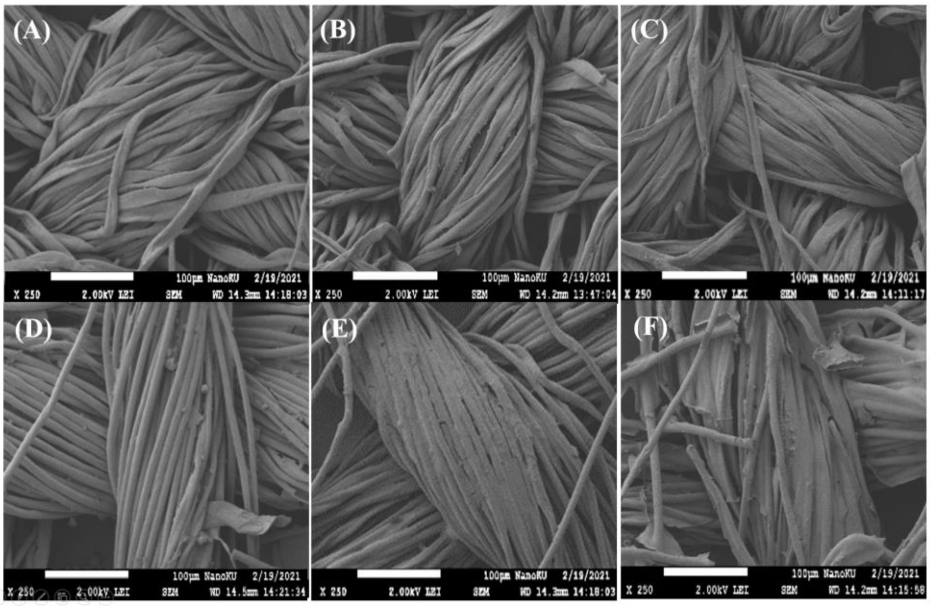


Figure 3 Surface morphology of coated textile mask lining; Muslin fabric (A), Muslin fabric coated with EFBL 0.125% w/v (B), Muslin fabric coated with EFBL 0.125:CS 0.25% w/v (C), Salo fabric (D), Salo fabric coated with EFBL 0.125% w/v (E), and Salo fabric coated with EFBL 0.125:CS 0.25% w/v (F).

3.3 Antimicrobial effect of extracted lignin

The antimicrobial effectiveness of lignin was investigated against *S. aureus*, a Gram-positive pathogenic bacterium, according to NCCLS 1999. The MIC and MBC values for the EFB lignin against *S. aureus* were 6,400 and 12,800 μg/mL, respectively, indicating greater antimicrobial efficiency than commercial lignin (MIC and MBC values of 10,000 and 20,000 μg/mL, respectively) [15]. It was reported that the antimicrobial characteristic of lignin comes from its methoxy groups [3]. While the lignin molecule and bacterial cell were in contact, lignin broke the cell walls. The bacteria then released internal fluid and died. However, the lignin concentrations or lignin levels on the textile surface were factors in the bacterial mortality rates [1].

The antimicrobial capability of the lignin coating on the Muslin fabric was examined using chitosan as a binder based on the two coating methods. Table 5 shows the reduction of bacterial growth after 24 h cultivation, with the electrostatic layer-by-layer deposition coating having 17.25% higher bacterial growth reduction than from soaking in the mixed solution. The higher reduction of bacterial growth might have been due to the antimicrobial properties of both lignin (with a negative charge) and chitosan (with a positive charge). Therefore, coating with lignin and chitosan in a series of layers, as in the layer-by-layer deposition coating method, might have promoted the antimicrobial activity of chitosan more than for the mixed solution.

Table 5 Reduction percentage of bacterial growth of test sample compared with control sample after 24 h.

Sample	Viable bacterial count		%Reduction
	0 h (CFU/mL)	24 h (CFU/mL)	
Control	3.93×10^5	2.29×10^9	
EFBL 0.125%: CS 0.25% w/v (mixed)	3.93×10^5	1.59×10^9	30.57
EFBL 0.125%: CS 0.25% w/v (layer-layer)	3.93×10^5	1.20×10^9	47.82

3.5 Fourier transform infrared spectroscopy analysis.

The chemical interaction of the coating solution (lignin and chitosan) and textile was investigated using Fourier Transform Infrared Spectroscopy Analysis (FT-IR) spectroscopic analysis, as shown in Figure 4. The typical peaks of lignin powder were observed at 3390 cm^{-1} (3030-3690 cm^{-1}), 2923 cm^{-1}, 1707 cm^{-1}, and 1220 cm^{-1} corresponding to -OH, C-H, C=O, and C-O stretching, respectively. The band of the aromatic structure was present at 1451-1601 cm^{-1}. The band of C-H vibrated at the 2nd and 6th positions of the syringyl structure at 838.7 cm^{-1}. The syringyl breathing band with a C-O stretching signal was observed at 1322 cm^{-1}. A band at 1118 cm^{-1} represented the aromatic C-H in plain deformation of the syringyl unit [1]. On the other hand, the typical peaks of chitosan powder were observed at 2882-2914 cm^{-1}, 1595 cm^{-1}, 1153 cm^{-1}, and 1085 cm^{-1} corresponding to C-H stretching, N-H bending of primary amine, C-O-C bridge stretching, and C-O stretching, respectively [25]. The N-acetyl group of chitosan was indicated by the C=O stretching of amide I at 1656 cm^{-1} and the C-N stretching of amide III at 1327.5 cm^{-1} [26].

The lignin and the chitosan coat on the textile caused a change in the intensity of some bands; for example, the interaction between the -OH of the lignin and textile by the absorption of hydrogen bonding at 3331 cm^{-1} [15]. As a result, hydrogen bonds formed and bound the lignin and textile. The slight shift in the intensity of lignin and chitosan was also the same for C-H stretching of the methylene group at 2893-2914 cm^{-1}. The band for C-H bending of the aromatic hydroxyl of lignin shifted from 1220 cm^{-1} to 1203 cm^{-1} of the lignin-coated textile. At C=O, lignin at 1707 cm^{-1} shifted toward higher wavenumber values at 1731-1734 cm^{-1} when lignin was incorporated in the textile [27]. For chitosan, the band range at 2800-3600 cm^{-1} was associated with N-H and O-H groups of chitosan on the textile through hydrogen bonding. The absorption peak at 1638 cm^{-1} of the chitosan showed the Schiff base C=N between the aldehydic carbonyl group of the textile and the amino group of the chitosan. The absorption at 1025-2890 cm^{-1} was stretching vibration of the C-H and C-O of the chitosan on the textile [28]. The absorption range 1370-1600 cm^{-1} was the peak of the free -NH2 group resulting from introducing the cationic site in the textile. The structures of lignin and chitosan have an antimicrobial function due to the phenolic hydroxyl and methoxy groups of lignin and the free amino group of chitosan [2,22]. In addition, chitosan has hydrophobic properties depending on N-acetyl groups [29].

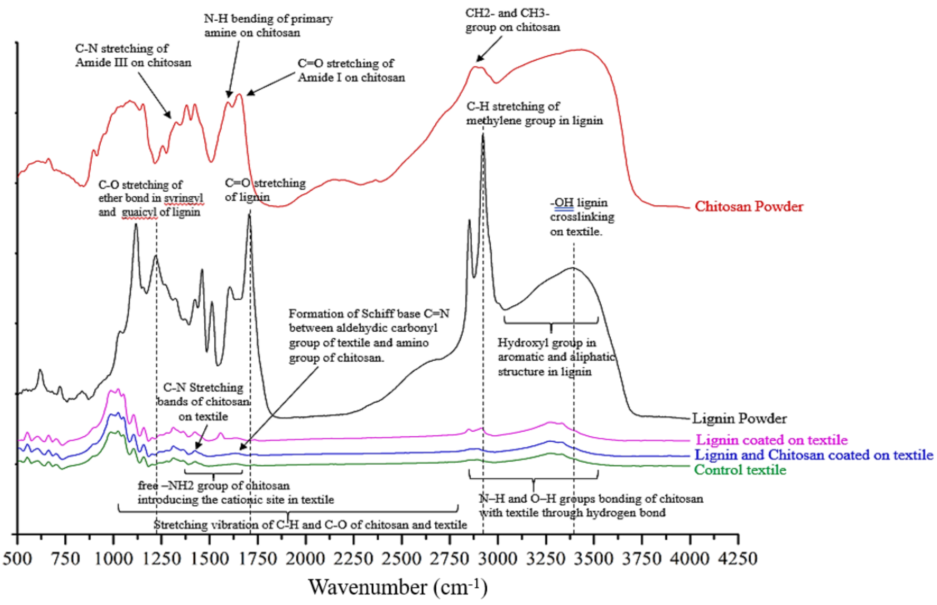


Figure 4 FT-IR spectra of lignin and chitosan-coated on textile.

3.6 Water contact angle

The water contact angle (CA) was measured to indicate the water barrier property (hydrophobicity) of the mask lining coated with lignin and chitosan. When a surface is hydrophobic, the water contact angle between a droplet of water and the textile surface is more than 90º [30]. The water barrier properties are an essential factor in an effective surgical mask. As shown in Figure 5, the CA of the Muslin fabric could not be detected. However, when the Muslin fabric was coated with lignin and chitosan, the water contact angle was 111.5º. Thus, the fabric's water barrier ability was increased due to the properties of the chitosan [30]. Therefore, CA measurements reinforced the positive effect of a chitosan-based coating on the textile mask lining.

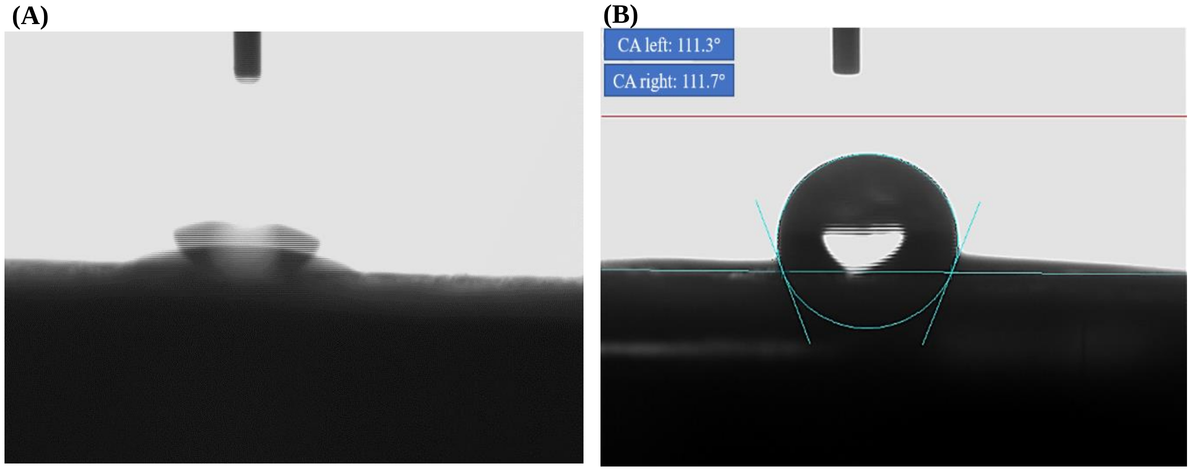


Figure 5 Water contact angle (CA) of Muslin fabric (A) and Muslin fabric coated with lignin and chitosan (B).

3.7 Air permeability

Permeability across the textile was determined from the pressure drop across a prototype similar to the method of Sunthornvarabhas et al. 2017 [1]. According to the industrial standards for a mask in Thailand, a maximum of 0.5 cm H_2O or 0.049 kPa is the maximum pressure drop acceptable for a general surgical mask (ASTM standard high barrier) [13]. The commercial textile mask had a pressure drop across the surface of 0.04 ± 0.01 kPa. When the developed masks with lining coated with lignin and chitosan were tested, the final products yielded similar pressure drops across the surface of 0.03 ± 0.01 kPa and 0.03 ± 0.01 kPa, respectively. However, using this coated textile mask resulted in a pressure drop higher than the standard value. Therefore, the period using the coated textile mask should be limited to avoid discomfort by the wearer.

3.8 Life cycle impact assessment (LCIA)

The evaluation considered the inputs and outputs of raw materials and energy consumption per functional unit using the Simapro software that provided information for the environmental impact assessment of the textile mask with a coated lining pad. ReCiPe Midpoint/Endpoint (H) was used in the environmental impact analysis focusing on global warming potential.

3.8.1 Environmental impact of lignin extraction process

The environmental impact assessment of the EFB lignin extraction process, as a component of the antimicrobial coating on a textile mask lining, was performed using the ReCiPe Midpoint/Endpoint (H) model from the Ecoinvent database. The process consisted of EFB preparation, pretreatment, and lignin extraction (Figures 6 and 7).

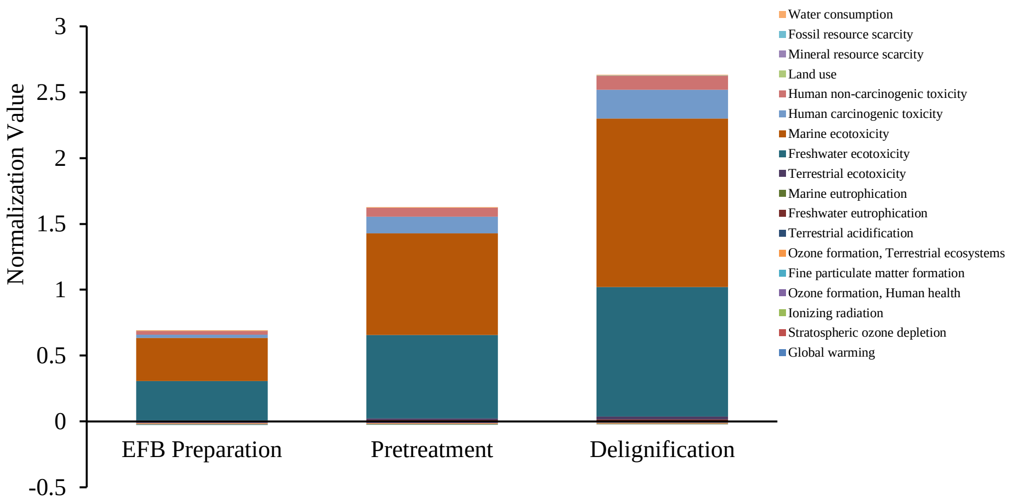


Figure 6 Normalization of lignin extraction process using ReCipe Midpoint (H) of 3.3024 g lignin production.

Table 6 Characterization of lignin extraction process using ReCipe Midpoint (H) of 3.3024 g lignin production.

Impact category	Unit	EFB preparation	Pretreatment	Delignification
Global warming	kg CO_2 eq	4.67	10.1	16.4
Ozone formation, Human health	kg NOx eq	0.00712	0.0148	0.0236
Fine particulate matter formation	kg PM2.5 eq	0.00519	0.0102	0.0156
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00726	0.0151	0.024
Terrestrial ecotoxicity	kg 1,4-DCB	6.96	14.5	22.9
Freshwater ecotoxicity	kg 1,4-DCB	0.383	0.785	1.21
Marine ecotoxicity	kg 1,4-DCB	0.364	0.806	1.33
Human carcinogenic toxicity	kg 1,4-DCB	0.339	0.599	0.855
Human non-carcinogenic toxicity	kg 1,4-DCB	4.41	9.54	15.4
Land use	m^2a crop eq	0.43	0.705	0.998
Water consumption	m^3	0.0194	0.0412	0.0678

Note: DCB= dichlorobenzene

The normalization in the Midpoint category of marine ecotoxicity had the highest impact, followed by freshwater ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity. The highest environmental impact was due to the delignification step from marine and freshwater ecotoxicity (1.33 and 1.21 kg 1,4- dichlorobenzeen (DCB) , respectively), followed by pretreatment and EFB preparation step in all impact categories. The other effects that resulted in lesser impacts from the lignin extraction process were global warming potential, and human non-carcinogenic toxicity of delignification step (31.1 kg CO_2 eq and 29.3 kg 1,4-DCB respectively). However, most of the impacts associated with lignin extraction and ecotoxicity were due to the electricity use in lignin production and the use of large quantities of water and agricultural wastewater that were slightly contaminated with the organic and inorganic chemicals used in the extraction.

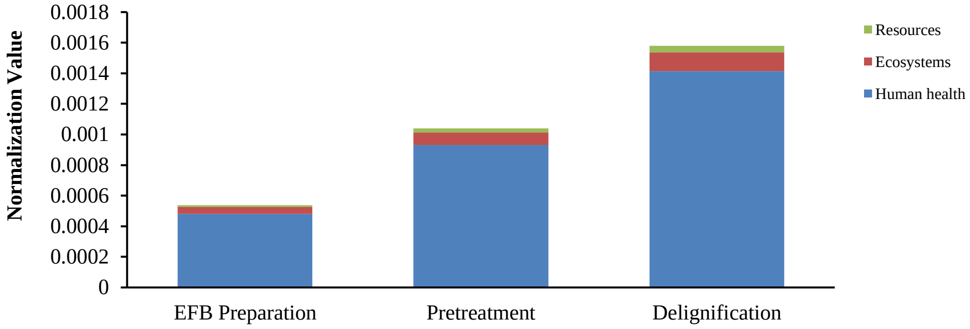


Figure 7 Endpoint categories of lignin extraction process from ReCipe Endpoint (H/A) of 3.3024 g lignin production.

The environmental impacts on Endpoint categories were long-term impacts in the human health that had the highest impact. The delignification had the substantially greatest impact, followed by pretreatment and EFB preparation. The highest impact of global warming on human health was due to the fine particulate matter formation, human non-carcinogenic toxicity, human carcinogenic toxicity, and water consumption. Most of the impact in all steps was due to the use of electricity and heat for the equipment and water used.

3.8.2 Environmental impact of tTextile mask with lining pad

The environmental impact assessment of textile masks coated with lignin and chitosan used the ReCiPe Midpoint/Endpoint (H) models to evaluate the impacts of global warming on climate change and energy consumption from raw material production to the disposal step after 1 year (cradle-to-grave approach).

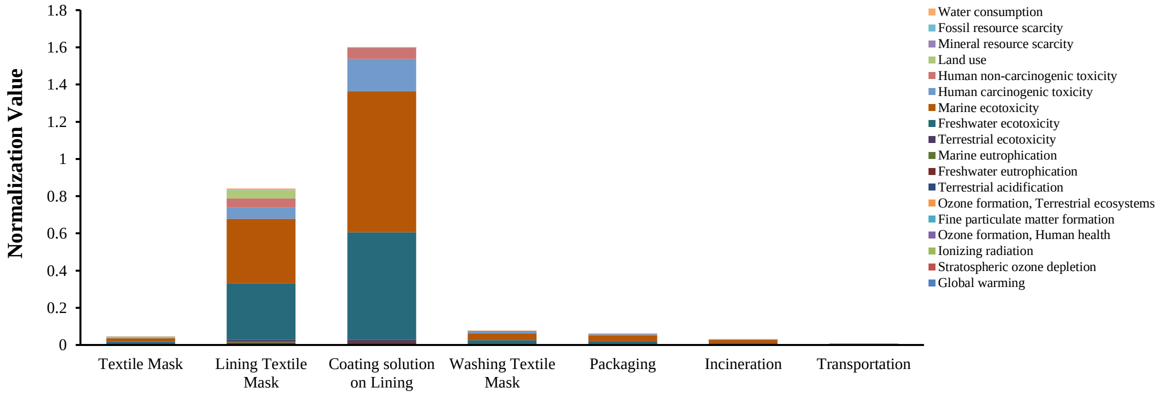


Figure 8 Midpoint impact categories of textile masks with lining coated with lignin and chitosan-based on ReCipe Midpoint (H) method on one-year life cycle of textile mask.

Table 7 Characterization of textile masks with lining coated with lignin and chitosan using ReCipe Midpoint (H) on one-year life cycle of the textile mask.

Impact category	Unit	Lining textile mask	Coating solution on lining
Global warming	kg CO_2 eq	0.00075	0.00122
Ozone formation, Human health	kg NOx eq	0.000849	0.000692
Fine particulate matter formation	kg PM2.5 eq	0.000499	0.000377
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00101	0.000818
Terrestrial ecotoxicity	kg 1,4-DCB	0.0108	0.0133
Freshwater ecotoxicity	kg 1,4-DCB	0.305	0.579
Marine ecotoxicity	kg 1,4-DCB	0.345	0.755
Human carcinogenic toxicity	kg 1,4-DCB	0.0636	0.177
Human non-carcinogenic toxicity	kg 1,4-DCB	0.0477	0.0576
Land use	m^2a crop eq	0.0429	0.000358
Water consumption	m^3	0.00951	0.000692

Normalization in the midpoint category of marine ecotoxicity had the highest impact, followed by freshwater ecotoxicity, human carcinogenic toxicity, and water consumption. The highest environmental impact was from coating solution (0.711 and 0.78 kg 1,4-DCB, respectively), followed by lining textile masks (0.374 and 0.356 kg 1,4-DCB, respectively). Most of the impact on the coating solution was due to electrical energy and water use for lignin production in the coating solution. In addition, 0.0024 g of lignin was used in the coating solution for a single lining pad, with 365 pieces/year of lining pad, followed by washing the textile mask and its eventual disposal via incineration. Machine washing had less environmental impact than handwashing; however, it required detergent and high energy consumption (60ºC washing) to heat the washing water [20].

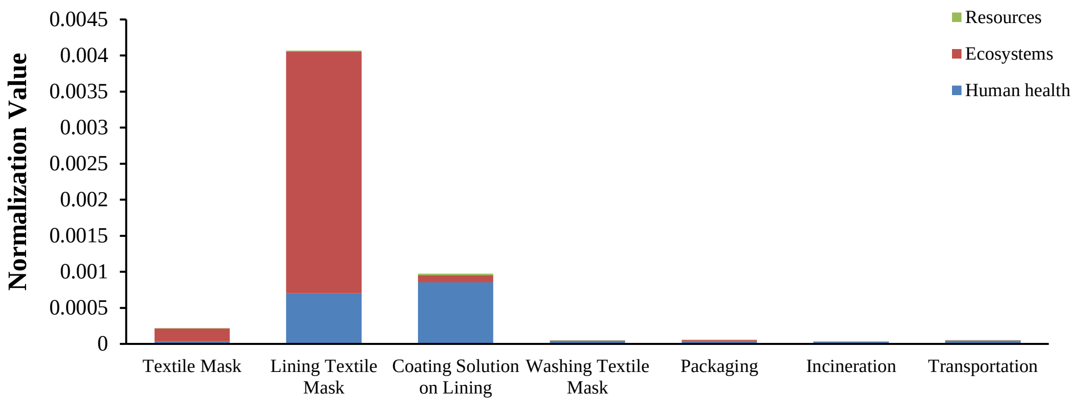


Figure 9 Endpoint impact categories of textile masks with lining coated with lignin and chitosan-based on ReCipe Endpoint (H) method on one-year life cycle of textile mask.

In the damage assessment based on Endpoint categories, long-term impacts from midpoint categories in the ecosystem and human health had the highest impact. The life cycle of most of the lining textile masks had the highest overall impact on ecosystem impact, as the land was required to produce the natural raw materials used in textile mask production (textile woven cotton). Human health effects were caused mainly by delicate particle matter formation, followed by global warming on human health, caused mainly by electrical energy, and water use in the lignin production of the coating solution on the textile mask. Most of the impacts were due to the large amounts of use natural resources required in production (365 pieces/year).

3.9 Cost estimate analysis

The estimated costs of raw materials throughout the production life cycle of EFB extracted lignin, including water, utilities and operational costs, involved electricity consumption of USD 0.16/kWh and utility water at USD 0.0005/L. In lignin extraction, 100 g of EFB was used to extract 3.3024 g of lignin powder. Therefore, the price per gram of lignin extract was assumed to be USD 6.39. When used as a raw material mixed with chitosan for the coating solution, the cost was USD 7.106/L. Therefore, the cost of lining the textile mask with coating solution was USD 0.0871/piece.

Table 8 Cost estimation of lining textile mask.

Material cost	Amount	Cost (USD)	Cost / unit (USD)
Lignin extraction			
EFB	100 g	-	-
H_2SO_4	22.397 mL	0.103	4.608/L
NaOH	6.88 g	0.066	9.6/kg
Distilled water	9.544 L	0.000477	0.0005/L , 9,000 W
Water utilities	873.861 L	0.4369	0.0005/L
Energy and utilities cost	20.6724 kWh	3.3075	0.16/kWh
Equipment cost per operation time	-	17.198	-
Total weight (EFB lignin)	3.3024 g	21.1118	6.39/g
Coating solution			
EFB lignin	0.12 g	0.767	6.39/g
NaOH	0.062 g	0.0006	9.6/kg
Chitosan	0.25 g	0.57	2.27/g
CH_3COOH	0.24 mL	0.0014	5.76/L
Ultrapure water	197.73 mL	0.048	0.0005/L , 9,000 W
Energy and utilities cost	0.00813 kWh	0.0013	0.16/kWh
Equipment cost per operation time	-	0.0329	-
Total volume	200 mL	1.4212	7.106/L
Lining textile mask			
Coating solution	4 mL	0.0284	7.106/L
Lining textile mask	190 cm^2	0.0279	1.47/m^2
Total cost	-	0.0562	0.0562/piece

Considering the cost of the four types of face mask over the life cycle, the lowest price (USD 2.50) was for the textile mask for machine washing the 4 pieces daily, followed by the disposable surgical mask (USD 29.2) and the textile mask with lining (USD 33.51). These latter two masks were priced in the same range at USD 4.3/piece. However, when considering textile masks with lining, the lining was used once a day with a coating added. Therefore, the price was separated and consisted of USD 2.50 for the textile mask, USD 10.18 for the lining, USD 20.513 for the coating solution, and USD 0.31 for machine washing throughout the life cycle.

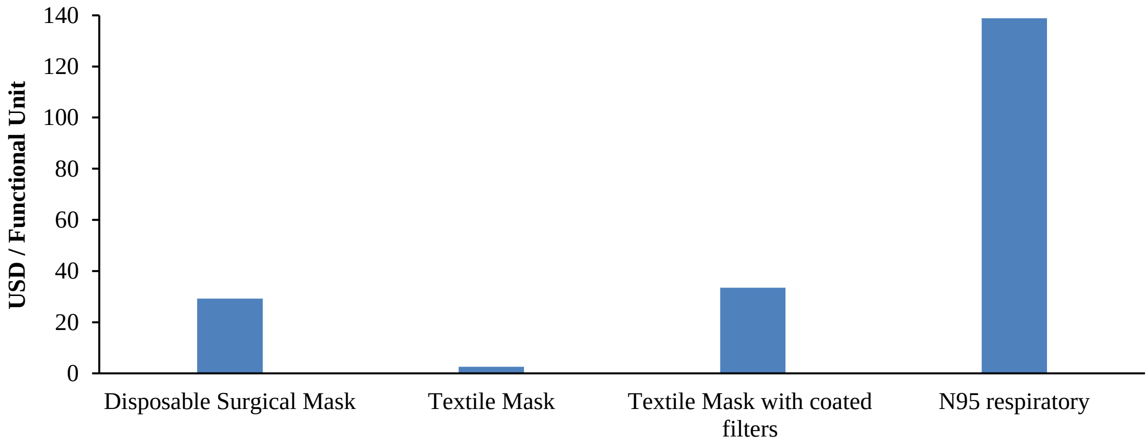


Figure 10 Total cost over life cycle of four types of face mask.

The results showed that the textile masks with lining pads coated with lignin and chitosan were the most suitable as they were environment-friendly and cost-effective. Furthermore, for efficacy in antimicrobial applications, the lignin and chitosan coating solution could prevent 47% of microbes; furthermore, the Department of Medical Sciences (Thailand) tested the 2-layer Muslin mask and found it was effective as a medical mask for applications requiring a waterproof fabric and fine particle filtration [31].

4. Conclusion

The lignin extracted from the EFB provided greater antimicrobial efficacy than commercial lignin. Coating the lining pad of textile masks made of Muslin cotton fabric, using chitosan as a binder between the lignin and the surface, enhanced the protection efficiency of the fabric masks due to the added antimicrobial, water barrier, and air permeability properties. In addition, the mask was environmental-friendly, having a low energy impact on global warming over the 1 year life cycle, and was inexpensive and cost-effective compared to the environmental impacts and efficiencies of the other tested masks (disposable surgical mask and N95 mask).

5. Acknowledgement

The Suksomboon Group, Thailand, provide the EFB raw material. This research was supported by: the Kasetsart University Research and Development Institute (KURDI), Bangkok, Thailand; the Biotechnology Mitrphol Group; and the Faculty of Engineering, Kasetsart University.

6. References

[1] Sunthornvarabhas J, Liengprayoon S, Suwonsichon T. Antimicrobial kinetic activities of lignin from Sugarcane bagasse for textile product. Ind Crops Prod. 2017;109:857-861.

[2] Espinoza-Acosta J, Torres-Chávez P, Ramírez-Wong B, López-Saiz C, Montaño-Leyva B. Antioxidant, antimicrobial, and antimutagenic properties of technical lignins and their applications. Bioresources. 2016;11(2):5452-5481.

[3] Sriroth K, Sunthornvarabhas J. Lignin from sugar process as natural antimicrobial agent. Biochem Pharmacol. 2018;7(1):1-4.

[4] Lee E, Song Y, Lee S, Antimicrobial Property and Biodegradability of Lignin Nanofibers. In: The 2014 World Congress on Advance in Civil, Environmental, and Materials Research (ACEM 14); 2014 Aug 24-28; Busan, Korea. 2014: p. 1-5.

[5] Etters J. Kinetics of dye sorption: effect of dyebath flow on dyeing uniformity. Am Dyest Report. 1995; 38-43.

[6] AOAC International. Official methods of analysis. 16th ed. Association of Official Analytical Chemists; 1999.

[7] Goering HK, Van Soest PJ. Forage fiber analyses (Apparatus, Reagents, Procedures, and Some Applications). In: Agriculture Handbook No. 379, Washingtom D.C.: U.S. Agricultural Research Service; 1970, p. 387-598.

[8] Medina J, Woiciechowski A, Zandona Filho A, Noseda M, Kaur B, Soccol C. Lignin preparation from oil palm empty fruit bunches by sequential acid/alkaline treatment--a biorefinery approach. Bioresour Technol. 2015;194:172-178.

[9] Kingkaew W, Saisriyoot M, Srinophakun P, Thanapimmetha A. Optimization of lignin production from agricultural Waste [Dissertation]. Bankok: Kasetsart University; 2020.

[10] Sluiter A, Hames B, Ruiz R, Scarlata C, Sluiter J, Templeton D, et al. Determination of structural carbohydrates and lignin in biomass. Colorado: National Renewable Energy Laboratory (NREL); 2012.

[11] Li H, Peng L. Antimicrobial and antioxidant surface modification of cellulose fibers using layer-by-layer deposition of chitosan and lignosulfonates. Carbohydr Polym. 2015;124:35-42.

[12] Sittikijyothin W, Printing paste preparation using seed gums as thickening agent for eco-friendly silk printing by natural dye from mangosteen rind [Report]: Chonburi ; Burapha University; 2016.

[13] Thai Industrial Standards Institute. Single-Use Hygiene Face Mask, https://testing.thaitextile.org/wp-content/uploads/2020/04/Single-use-hygienic-face-masks-Test-List-WEB.pdf; 2019 [Accessed 20 July 2021].

[14] Hult E, Ropponen J, Poppius-Levlin K, Ohra-Aho T, Tamminen T. Enhancing the barrier properties of paper board by a novel lignin coating. Ind Crops Prod. 2013;50:694-700.

[15] Inna K, Sunthornvarabhas J, Thanapimmetha A, Saisriyoot M, Srinophakun P. Natural antimicrobial lignin in polyvinyl alcohol and polyvinylpyrrolidone film for packaging application. Materials Science Forum. 2018;936:105-109.

[16] Schmutz M, Hischier R, Batt T, Wick P, Nowack B, Wäger P, et al. Cotton and surgical masks-what ecological factors are relevant for their sustainability? Sustainability. 2020;12(24):1-13.

[17] Boix Rodríguez N, Formentini G, Favi C, Marconi M. Engineering design process of face masks based on circularity and life cycle assessment in the constraint of the COVID-19 pandemic. Sustainability. 2021;13(9):1-26.

[18] World Health Organization. Shortage of personal protective equipment endangering health workers worldwide, https://www.who.int/news-room/detail/03-03-2020-shortage-of-personalprotective-equipment-endangering-health-workers-worldwide; 2020 [Accessed 20 July 2021].

[19] Sunthornvarabhas J, Liengprayoon S, Lerksamran T, Buratcharin C, Suwonsichon T, Vanichsriratana W, et al. Utilization of lignin extracts from sugarcane bagasse as bio-based antimicrobial fabrics. Sugar Tech. 2018;21(2):355-363.

[20] Allison A, Ambrose-Dempster E, Domenech Aparsi T, Bawn M, Casas Arredondo M, Chau C, et al. The environmental dangers of employing single-use face masks as part of a COVID-19 exit strategy. UCL Open: Environment Preprint. 2020;1-44.

[21] Sun Y, Cheng J. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresour Technol. 2002;83:1-11.

[22] Sunthornvarabhas J, Rungthaworn P, Sukatta U, Juntratip N, Sriroth K. Antimicrobial tendency of bagasse lignin extracts by raman peak intensity. Sugar Tech. 2020;22(4):697-705.

[23] Rashid T, Gnanasundaram N, Appusamy A, Kait C, Thanabalan M. Enhanced lignin extraction from different species of oil palm biomass: kinetics and optimization of extraction conditions. Ind Crops Prod. 2018;116:122-136.

[24] Davies A, Thompson K, Giri K, Kafatos G, Walker J, Bennett A. Testing the efficacy of homemade masks: would they protect in an influenza pandemic? Disaster Med Public Health Prep. 2013;7(4):413-418.

[25] Knidri H, Belaabed R, khalfaouy R, Laajeb A, Addaou A, Lahsini A. Physicochemical characterization of chitin and chitosan producted from *Parapenaeus longirostris* shrimp shell wastes. J Mater Environ Sci. 2017;8(10):3648-3653.

[26] Fernandes Queiroz M, Melo K, Sabry D, Sassaki G, Rocha H. Does the use of chitosan contribute to oxalate kidney stone formation? Mar Drugs. 2014;13(1):141-58.

[27] Azhar N, Adrus N, Wan Rahman W, Majid R. Lignin-coated polystyrene/trichloromethylsilane absorbent for oil spill cleanup. Sains Malays. 2020;49(9):2141-2148.

[28] Wang S, Jing Y. Effects of a chitosan coating layer on the surface properties and barrier properties of kraft paper. Bioresources. 2016;11(1):1868-1881.

[29] Varma R, Vasudevan S. Extraction, characterization, and antimicrobial activity of chitosan from horse mussel modiolus modiolus. ACS Omega. 2020;5(32):20224-20230.

[30] Vikele L, Laka M, Sable I, Rozenberga L, Grinfelds U, Zoldners J, et al. Effect of chitosan on properties of paper for packaging. Cellul Chem Technol. 2017;51(1-2):67-73.

[31] Department of Medical Sciences Ministry of Public Health. Department of Medical Sciences revealed the results of the fabric mask performance test, https://www3.dmsc.moph.go.th/post-view/705; 2021 [Accessed 20 July 2021].