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Testing the Effectiveness of Various Fabrics for Use in Protective Face Coverings

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Testing the Effectiveness of Various Materials for Use in Protective Face Coverings

Submitted to:

William Honors College

The University of Akron

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Executive Summary

Recommendations and mandates for the use of facial coverings have been heavily implemented due to the COVID-19 pandemic. Readily available facemasks are typically made of paper or common household fabrics, but the effectiveness of these mask designs is frequently questioned. The goal of this research was to determine the most effective material to be used in face coverings to reduce the transmission rate of COVID-19.

Seven different fabrics were tested in this study to determine the optimal fabric for reducing the spread of the SARS-CoV-2 virus. This analysis was based on material wettability and droplet adherence, properties which were expected to provide an indication about the likelihood of droplet transmission through facemasks. To evaluate wettability, 10 μL water droplets were placed onto the surface of each fabric and a contact angle was determined for each material based on the characteristic radius of the average droplet area. Droplet adherence was determined by spraying the fabrics with a fine mist of dyed water and counting the number of droplets on the fabric. These droplets were also measured to generate size distributions for all applicable materials.

Of the materials tested, the decyltrichlorosilane (DTS) modified cotton, perfluorotrichlorosilane (FTS) modified cotton, and polyester were determined to be the most effective at preventing droplets from penetrating through the fabric during wettability testing. The contact angles of water droplets on these materials (based on the characteristic radii) were 106°, 93°, and 93°, respectively. For all other materials, the water droplets passed through the fabric with imbibition rates ranging between 0.010 μL/s to over 10 μL/s. Materials exhibited similar behavior when spraying a fine mist of water at the fabrics; droplets adhered to the surfaces of DTS modified cotton, FTS modified cotton, and polyester samples. The number of

droplets adhered was counted for each material and normalized based on one gram of water sprayed at the fabric (123 drops for DTS modified cotton, 83 drops for FTS modified cotton, and 55 drops for polyester). Average water droplet radii were determined based on area measurements and computed values were 0.66 mm for DTS modified cotton, 0.54 mm for FTS modified cotton, 0.76 mm for polyester. For all other materials, droplets either passed through or were absorbed into the fabric.

Based on the material wettability and droplet adherence studies, DTS modified cotton, FTS modified cotton, and polyester are the best materials to be used in a facemask (of the seven fabrics tested) in terms of ability to block droplets. The safety implications of these materials were not studied but is another key aspect in the material selection process. It was also determined that the greater initial velocity of water droplets in the adherence study led to higher imbibition rates but had no effect on the droplets' ability to penetrate through the fabric or adhere to the surface.

The work presented here can potentially help facemask users in choosing a more effective fabric and reduce the likelihood of virus transmission. The motivation for the research was related to COVID-19, but the conclusions are applicable to other viruses which can be passed through droplet transmission.

Future experimentation could include the testing of additional materials and a further refined procedure. Controlling fabric properties such as thickness or thread type would also be beneficial so that performance differences could be solely attributed to the material rather than other factors. In addition, the use of a highly accurate lab scale would improve the quality of the mass balance in both testing stages and likely lead to improved results.

Given that this work was also used as a William Honors College research project, various technical and career skills were gained throughout its completion. Although a lot of the technical background was not discussed in the curriculum, there was overlap between the fundamentals of this project with concepts from many courses (Chemistry, Thermodynamics, Fluid and Thermal Operations and Transport Phenomena) that are part of the program. In addition, the project has reinforced non-technical skills such as working independently and managing time efficiently. Finally, the report has provided another opportunity to practice technical writing, a skill that has been emphasized throughout the chemical engineering curriculum.

Future students in a similar position would likely benefit if they were able to submit their project proposals sooner. Gaining project approval by the summer semester before a student's final year would allow students to work on the project during a more relaxed semester (typically a co-operative education work assignment). It was more challenging to execute project work during academic semesters, especially to complete the necessary experimentation. A final recommendation is to stay organized and take notes throughout the completion of the project. It may be beneficial to keep a written log or lab notebook. Having detailed notes made it easier to write the final report, rather than trying to remember the details of experiments which were conducted months prior.

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Introduction/Background

As a result of the COVID-19 pandemic, facemask requirements have been heavily implemented to help slow the spread of the virus. Oftentimes, these requirements only specify the obligation of the user to cover the nose and mouth with a face covering. While concealing these areas is important, the material of the mask also plays a key role in preventing the spread of COVID-19.

The aim of this research was to determine the most effective fabric to be used in a homemade facemask. While the main motivation for the study was to determine a mask design to mitigate the spread of the SARS-CoV-2 virus, the research is applicable to preventing the spread of other respiratory infections which are spread through modes of droplet transmission. Examples of such diseases are tuberculosis, measles, and chickenpox.[1]

Similar research has been conducted by research groups to determine the optimal design for a face covering, a large portion of which has focused on creating multi-layer masks using various household materials. One such study performed at the University of Illinois showed the importance of layering by examining droplet penetration through various materials. When using T-shirt material, a single layer stopped 40% of simulated virus droplets while 98% of particles were blocked when adding a second layer.[2] In a separate study performed by Banerjee et. al, a suggestion for a three-layer homemade mask was provided based on testing results. The study showed that two layers of hydrophobic polypropylene outlining a hydrophilic cellulosic layer was the most effective design that was tested.[3] In another analysis performed at Northeastern University, a multi-layer facemask was utilized and showed better results than an N95 respirator when spraying nanoparticles at the face coverings. The layered design included terry cloth, quilting cotton, and flannel.[4]

The research presented here is more focused on the surface interaction between the material and the droplets. While the ability of a mask to stop droplets from penetrating is obviously the most important thing to understand for the user, this study takes a more fundamental approach to understanding performance differences among these materials.

Many of the fabrics tested were ordinary household fabrics used abundantly in face coverings (cotton, quilting cotton, terry cloth, flannel, and polyester). Two additional materials were prepared in a lab and used as comparisons during the study. These fabrics were cotton-based and coated with various hydrophobic organosilanes to decrease the wettability of the fabrics. The modifiers used were *n*-decyltrichlorosilane (DTS) and perfluorodecyl-1*H*,1*H*,2*H*,2*H*-trichlorosilane (FTS), and their chemical structures are shown in **Figure 1**.

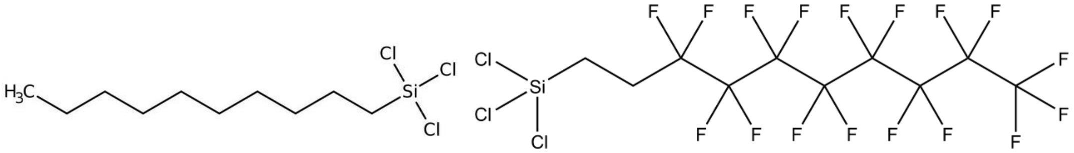

Figure 1. Chemical structures of n-decyltrichlorosilane (left) and perfluorodecyl-1H,1H,2H,2H-trichlorosilane (right).[5,6] These surface modifiers are denoted by the abbreviations DTS and FTS, respectively.
Images reprinted from:
(Left Image)-1H,1H,2H,2H-Perfluorodecyltrichlorosilane 5g. (2021). Retrieved from P212121: https://store.p212121.com/1h-1h-2h-2h-perfluorodecyltrichlorosilane/
(Right Image)- Alfa Aesar™ n-Decyltrichlorosilane, 97%. (n.d.). Retrieved from Fisher Scientific: https://www.fishersci.com/shop/products/n-decyltrichlorosilane-97/AAL0591209

The goal was to first observe the behavior of droplets on the surface of the fabric to determine the wettability of the material. A classification of material wettability based on the contact angle between water droplets and the material is provided in **Figure 2**. The subsequent part of the study consisted of evaluating water droplet adherence of same fabrics by spraying the materials with a dyed water solution.

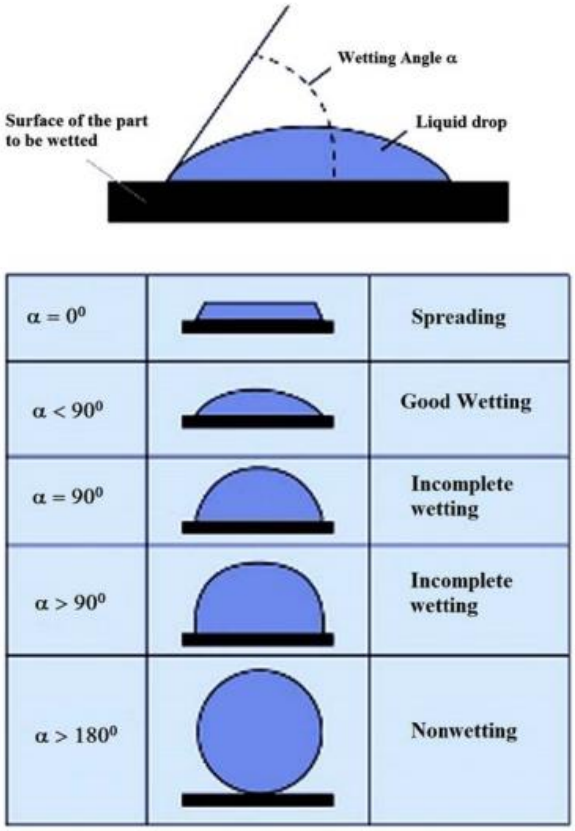

Figure 2. Summary of material wettability based off the contact angle between the surface and a spherical droplet.[7]
Image reprinted from [Thomas, S., Thomas, R., Zachariah, A. K., & Mishra, R. K. (Eds.). (2017). *Thermal and rheological measurement techniques for nanomaterials characterization*. ProQuest Ebook Central https://ebookcentral.proquest.com]

It was hypothesized that materials with a higher contact angle (less wettable materials) would have more water droplets adhere to the surface (rather than absorbing into the fabric) when sprayed with a mist. An intermediate goal of the study was to develop a mathematical correlation between the droplet adherence and contact angle (if possible). The ultimate objective was to determine the optimal material to be used in a face covering among the seven tested in the study.

Experimental Methods

Types of fabrics

Types of fabrics evaluated included common household fabric materials such as cotton, polyester, terry cloth, quilting cotton, and flannel. Additional cotton samples modified with hydrophobic organosilanes were also tested. A summary of the materials used during the study is shown in **Table 1**.

Table 1. Summary of the materials tested, including the source and product code if applicable.

Material	Cotton	Polyester	Terry Cloth	Quilting Cotton	Flannel	DTS Modified Cotton	FTS Modified Cotton
Source	Dr. Newby's Lab	JOANN Fabrics	JOANN Fabrics	JOANN Fabrics	JOANN Fabrics	Dr. Newby's Lab	Dr. Newby's Lab
UPC	N/A	16524654	1136-6572	1693-4820	1791-4904	N/A	N/A

Wettability Testing

To determine the wettability of materials, contact angles or imbibition rates were obtained for each of the types of fabrics outlined above. For each trial, a syringe pipette was used to draw out 10.0 μL of deionized water. The water was transferred onto a fabric sample, which was resting on a flat surface. A digital microscope was used to enlarge the image of the water droplets, and a ruler was also used to determine the magnification of the images taken using Yawcam (a software for taking digital images). The setup for the wettability testing is shown in **Figure 3**.

Figure 3. Experimental setup for the wettability testing. The digital microscope was connected to the laptop using a USB cable, and the Yawcam application was used to take photographs throughout the trials.

Depending on the material, droplets may either penetrate through the fabric or remain on the surface. For drops that passed through the fabric, the time required to penetrate through the fabric was recorded to calculate the imbibition rate. For droplets that did not pass through the fabric, the contact angle was determined from analyzing the images captured from Yawcam. For the contact angle analysis, ImageJ (a measuring software) was used to determine the characteristic size of the droplet, which is shown in **Figure 4**.

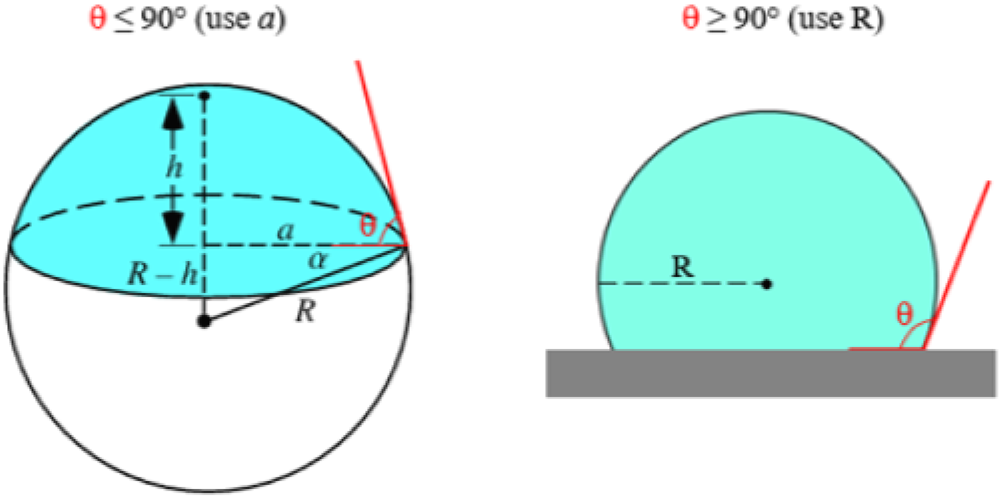

Figure 4. Schematic showing the characteristic droplet dimension to be used for the contact angle correlation.

Image J was used to set a scale of a known dimension using the ruler measurements as a reference. After setting the scale, the ellipse tool was used to outline the droplet as closely as possible, as shown in **Figure 5**. The software was used to compute the area of this ellipse, and the radius of an equivalent circle was calculated to be used in the contact angle correlation.

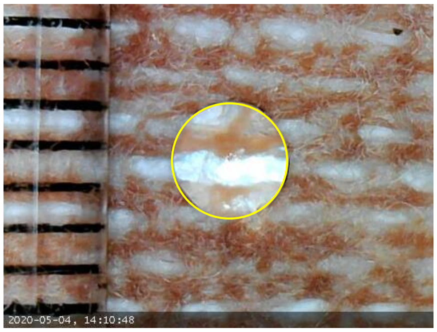

Figure 5. Representation of Image J analysis for a single droplet. The ruler was included in each image to scale the measurements properly. Each droplet was outlined (shown in yellow) using the ellipse tool and the software computed the area of the drawn ellipse.

Droplet Adherence Testing

For each fabric, a 3” × 3” sample was cut for the droplet adherence testing. A spray bottle was filled with purified water and three drops of food dye were added. For each fabric, the sample was mounted to a piece of cardboard hanging vertically, and the spray bottle was placed 36 inches in front of the fabric sample. The spray bottle nozzle was adjusted to generate a fine mist, and the sample was sprayed with the water two times. The setup for the droplet adherence testing is represented in **Figure 6**. A mass balance on the water was performed by taking the mass of the spray bottle before and after spraying the fabric so that the number of droplets adhered could be normalized to the mass of the water sprayed. The analysis was completed by generating images of the fabric samples and measuring the areas of each droplet that adhered to the surface. These areas were converted into the radius of a characteristic sphere, and size distributions of the droplets were created for each sample in which the droplets adhered to the surface.

Figure 6. Experimental setup for the droplet adherence testing. A kitchen scale was also used to track how much water was sprayed at each fabric sample.

Data and Results

Wettability Testing

When testing the wettability of the materials, water droplets remained on the surface for extended periods for just three fabrics. Those materials were DTS modified cotton, FTS modified cotton and polyester. For these fabrics, the area of the droplets was measured using ImageJ and a contact angle was the computed. The data for these fabrics is summarized in **Table 2**.

Table 2. Summary of wettability testing for materials in which the droplets stayed on the surface of the fabric over extended periods.

Material	A_i = Droplet Area of the ith Droplet					A_{avg} (mm^2)	R (mm)	Θ (deg)
	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	A_5 (mm^2)			
Cotton	-	-	-	-	-	-	-	-
DTS Modified Cotton	7.2	7.2	6.6	7.4	7.2	7.1	1.5	106
FTS Modified Cotton	7.9	8.4	8.4	8.9	8.7	8.5	1.6	93
Quilting Cotton	-	-	-	-	-	-	-	-
Flannel	-	-	-	-	-	-	-	-
Polyester	8.5	8.5	8.7	8.4	8.5	8.5	1.6	93
Terry Cloth	-	-	-	-	-	-	-	-

For materials in which the droplets did not remain on the fabric surface and passed through the material, imbibition rates were determined. The relevant data for these materials (cotton, quilting cotton, flannel, and terry cloth) are summarized in **Table 3**.

Table 3. Summary of wettability testing for materials in which the droplets passed through the fabric samples.

Material	t_i = Time for Imbibition of the i^{th} Droplet					t_{avg} (s)	Rate of Imbibition (µL/s)
	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_5 (s)		
Cotton	807	500	1015	1735	880	987	1.0E-02
DTS Modified Cotton	-	-	-	-	-	N/A	N/A
FTS Modified Cotton	-	-	-	-	-	N/A	N/A
Quilting Cotton	55	54	45	55	55	52.8	0.2
Flannel	3.1	2.9	2.6	3.1	3.4	3.0	3.3
Polyester	-	-	-	-	-	N/A	N/A
Terry Cloth	<1	<1	<1	<1	<1	<1	>10

Droplet Adherence Testing

When testing for droplet adherence on the different materials, it was found that droplets adhered to the surface of three types of fabrics: DTS modified cotton, FTS modified cotton, and polyester. **Figure 7** summarizes the droplet behavior on the different fabric samples used during the experimentation.

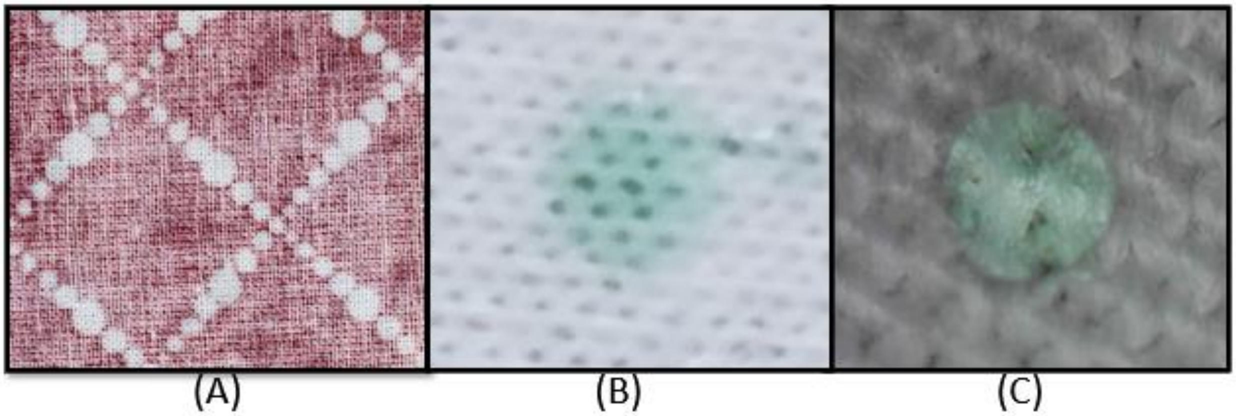

Figure 7. Summary of droplet behavior on different surfaces. In the leftmost image (A), the droplet passes through or is absorbed without staining the fabric, which was the outcome for quilting cotton and flannel. The middle image (B) shows a droplet passing through or being absorbed by the fabric while staining it, which was the case for cotton and terry cloth. The rightmost image (C) shows a droplet adhering to the surface of the fabric which occurred in the DTS modified cotton, FTS modified cotton, and polyester samples.

For the DTS modified cotton, FTS modified cotton, and polyester, the number of droplets adhered to the surface was normalized based on one gram of water being sprayed at the fabric to generate a comparison, which is shown in **Figure 8**. Size distributions for the droplets were also generated for these three fabrics and are depicted in **Figure 9**.

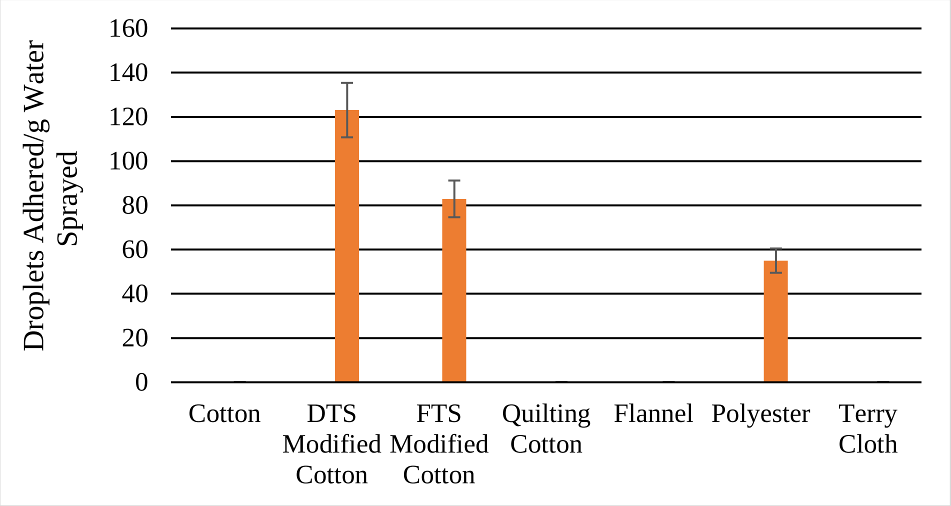

Figure 8. Comparison for the number of droplets adhered to the fabric surface for the seven materials tested, normalized based on one gram of water sprayed at the fabric surface. For cotton, quilting cotton, flannel, and terry cloth, all the droplets passed through or were absorbed by the fabric rather than sticking to the surface.

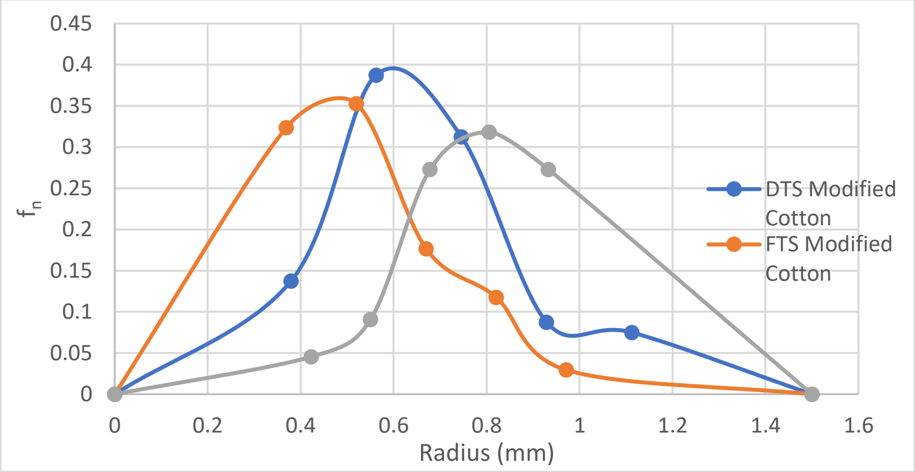

Figure 9. Number distribution of droplet size for water particles that adhered to the surface of DTS modified cotton, FTS modified cotton, and polyester samples. Average characteristic radii were 0.66 mm, 0.54 mm, and 0.74 mm, respectively.

After completing the testing, a linear regression was performed to develop a relationship between the droplet adherence and contact angle testing results. A linear trend for the data is shown in **Figure 10** and a regression summary for the fit provided is shown in **Table 4**.

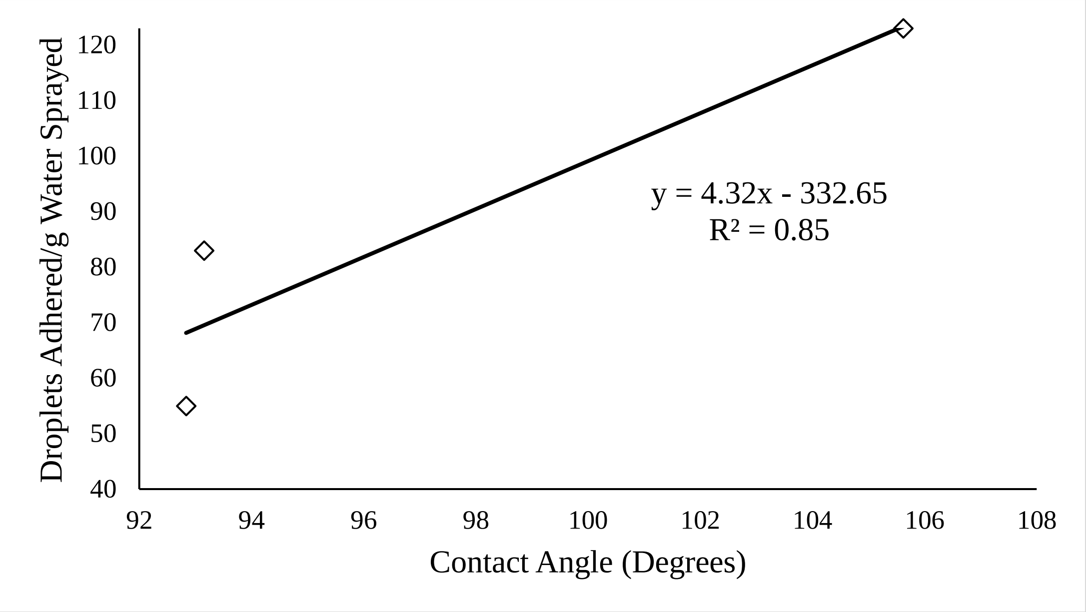

Figure 10. Normalized droplet adherence plotted as a function of contact angle including the line of best fit from the linear regression.

Table 4. Regression summary for the line of best fit between normalized droplet adherence and contact angle.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R^2	0.70
Standard Error	18.82
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1982	1982	5.59	0.25
Residual	1	354	354		
Total	2	2336			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-333	178	-1.87	0.31	-2591	1926
ϴ (deg)	4.32	1.83	2.37	0.25	-18.9	27.5

Discussion/Analysis

When testing the wettability of materials, a clear division existed between the different types of fabrics. The modified cotton samples (both DTS modified and FTS modified) as well as the polyester sample proved to be the most effective at keeping the water droplets at the surface rather than passing through or absorbing into the material. The other samples were more hydrophilic, and the water droplets passed through or were absorbed into the fabric at varying rates.

In the subsequent portion of the testing (droplet adherence testing), the spraying of water accelerated the imbibition process of the droplets but did not alter the qualitative outcome (imbibition or adherence) for any of the fabrics. It was hypothesized that the initial velocity of the droplet in this experiment would not alter the wettability significantly, and this result is a key takeaway from the experimentation. The consistency of the DTS modified cotton, FTS modified cotton, and polyester in preventing droplets from passing through the fabric proves that these materials would be beneficial to be used in facemasks.

Due to the limited number of data points, quantitative trends were not as apparent when analyzing the data. It was believed that contact angle and droplet adherence would follow a negative relationship, and the opposite was found to be true. This trend could likely be explained by a small sample size (over a small region of contact angles) and significant error which was involved in both the wettability and droplet adherence testing. It is also worth noting that both coefficients (linear and constant terms) were found to be insignificant at the 0.05 significance level, so data does not strongly support the trend provided by the line of best fit.

As mentioned in the preceding paragraph, there were many sources of error in each part of the testing. In the wettability testing, the main error source was the uncertainty in the amount of water dispensed and transferred onto the surface of the fabric. **Figure 11** illustrates how the volume of the droplet impacts the relationship between the contact angle and characteristic radius of the droplet. A high accuracy scale could have been used to perform mass balances and minimize this type of error, but experiments were designed for completion outside of the lab due to the COVID-19 pandemic. Likely the largest source of error was the inconsistency when spraying the dyed water at the fabrics. Once again, a high precision scale would have been useful for mass balance purposes, and the number of droplets adhered could be normalized to the mass of water that contacted the surface, rather than the mass of the water sprayed. Another source of error that was present in both stages of testing was the measurement of droplets using ImageJ, but this source is believed to contribute to minimal error compared to the other sources.

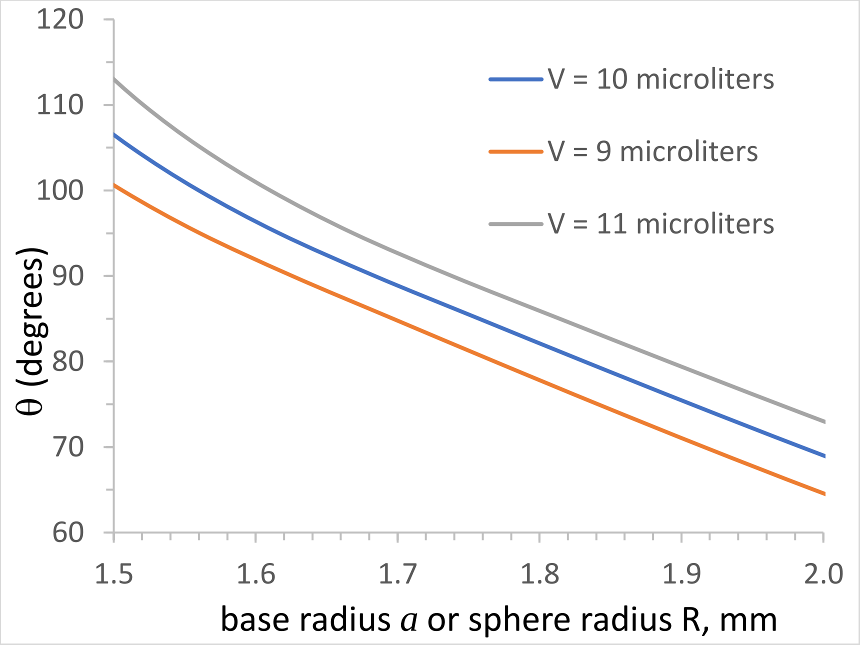

Figure 11. Relationship between contact angle and characteristic radius for different volumes of water shows that an error of 1 microliter in the transfer corresponds to an error in the contact angle of about five degrees (over the typical size range found during testing).

Based on the testing completed, DTS modified cotton, FTS modified cotton, and polyester were superior to the other materials tested for use in a facemask. Among these materials, performance differences were observed in the contact angle during wettability testing, the normalized number of droplets adhered, and the size distribution of the droplets adhered. To determine the best material out of these three, additional testing would likely need to be performed. However, based on the data presented here and the relative error in each of these methods, it was determined that FTS modified cotton is likely the best material. The size distribution of droplets on the fabric showed that the material is the least wettable assuming the droplet sizes from the sprayer were consistent throughout the trials. This assumption is likely accurate given that the distance from the spray bottle to the fabric was fixed and that the nozzle was not adjusted during the testing.

One aspect that should be considered moving forward is the safety element of using these materials, particularly for the modified surfaces. Understanding how these materials can affect a user's skin is essential, as is the process safety in producing these modified fabrics.

While fabric wettability has a major impact on the effectiveness of a facemask and was a focus in this study, there are additional variables which have an impact on the results of the tests which were not considered in this analysis. These variables include the fabric thickness, fabric type (woven vs non-woven), and thread separation. **Figure 12** shows the approximate fabric thicknesses for the materials tested in this study.

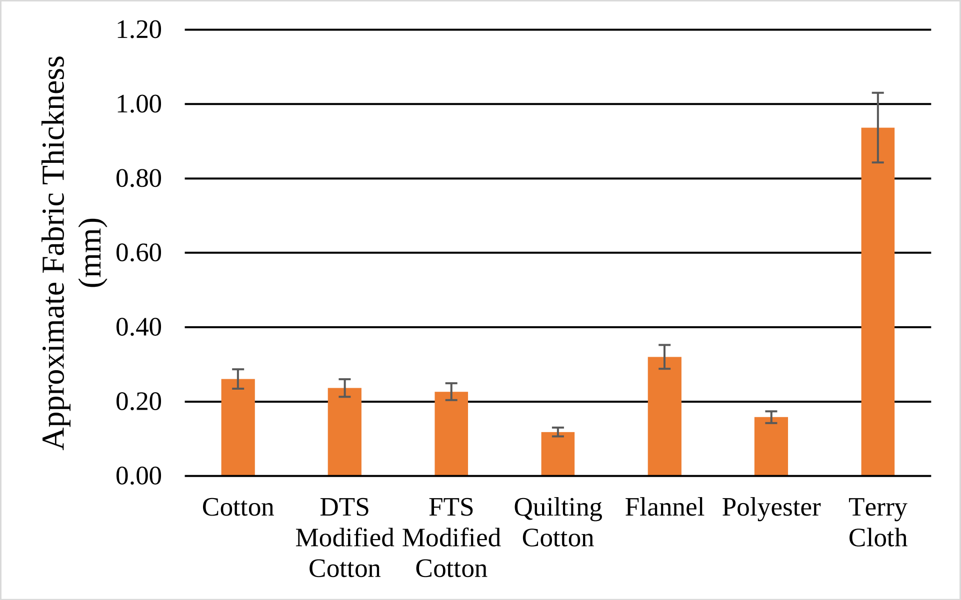

Figure 12. Comparison of the approximate thicknesses of the fabrics used in the wettability and droplet adherence experiments. 10% error bars were selected to account for error in the measuring process, but there are clear differences between the fabric thicknesses.

To expand upon this study, future experimentation could utilize additional materials and minimize the error sources that were present due to working outside of a lab environment. If possible, fabric sample specifications (thickness, separation, etc.) could be controlled to limit additional factors which affect the material performance during testing. If these specifications cannot be controlled, these parameters could be quantified to correlate how they affect droplet adherence. Initially, an artificial mucus made of gelatin and corn syrup was used to evaluate the droplet adherent on the fabrics. However, due to the inconsistency in viscosity and plugging of the nozzle during spraying, a decision was made not to use it. In the future, an artificial mucus sprayed out of an airbrush that could result in consistent spraying should be considered. Using all plain, white fabrics would also be beneficial to make droplets more visible when counting them. Additional mass balance data would also be advantageous if appropriate lab scales are available. Finally, replicating similar studies from literature using the top performing materials would be useful in future work.

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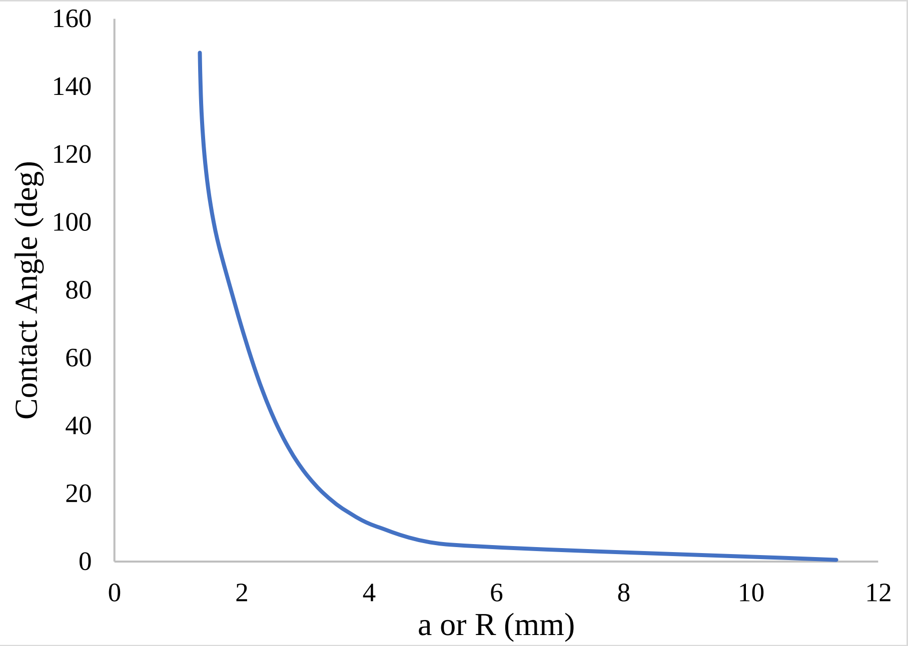
Appendix A: Contact Angle Correlation

a or R (mm)	Θ (deg)
1.342	150
1.347	145
1.354	140
1.363	135
1.376	130
1.393	125
1.414	120
1.441	115
1.473	110
1.513	105
1.56	100
1.616	95
1.684	90
1.757	85
1.832	80
1.907	75
1.984	70
2.065	65
2.149	60
2.238	55
2.335	50
2.441	45
2.559	40
2.694	35
2.852	30
3.046	25
3.294	20
3.636	15
4.171	10
5.262	5
11.342	0.5



Appendix B: Mass Balance Data

Material	Cotton	DTS Modified Cotton	FTS Modified Cotton	Quilting Cotton	Flannel	Polyester	Terry Cloth
m_{before} (g)	281.79	280.39	279.74	273.95	274.61	273.32	278.51
m_{after} (g)	280.39	279.74	278.51	273.32	273.95	272.92	277.09
m_{water} (g)	1.4	0.65	1.23	0.63	0.66	0.4	1.42
$n_{droplets}$	0	80	102	0	0	22	0
$n_{droplets}$/g H_20	0	123	83	0	0	55	0