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Permeability analysis of masks developed for biological emergency and disaster response: a laboratory study

Análise de permeabilidade de máscaras desenvolvidas para enfrentamento de emergências e desastres biológicos: pesquisa laboratorial

Análisis de permeabilidad de mascarillas desarrolladas para enfrentar emergencias y desastres biológicos: investigación de laboratorio

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ABSTRACT
Objective: to analyze the air permeability of masks developed for biological emergency response. **Method**: laboratory study involving tests on cloth masks with a cellulose filter element (LisLu20®), produced during the COVID-19 pandemic, disposable surgical masks, PFF2/N95 masks, and homemade cotton masks. Analyses were conducted in May and June 2020, following ASTM D 737:2018 standards **Results:** six tests were conducted on ten units of each mask. LisLu20® (a) - two layers: 8.6 cm³/s/cm²; LisLu20® (b) - three layers, Asian style: 6.2 cm³/s/cm²; LisLu20® (c) - three layers, PFF2/N95 style: 4.8 cm³/s/cm²; Disposable surgical mask: 18.0 cm³/s/cm²; PFF2/N95 mask: 10.2 cm³/s/cm²; Cotton knit mask: 31.1 cm³/s/cm². **Conclusion**: LisLu20® masks provided a physical barrier and served as a preventive method to reduce respiratory infection risks. As a low-cost, sustainable domestic product, they offered complementary emergency support to mitigate the shortage of disposable surgical masks.
Descriptors: Coronavirus Infections; COVID-19; Personal Protective Equipment; Masks; Supply.

RESUMO
Objetivo: analisar permeabilidade do ar de máscaras desenvolvidas para enfrentamento de emergências biológicas. **Método:** estudo laboratorial, com testes de modelos de máscaras de tecido com inserção de elemento filtrante em celulose (LisLu20®), confeccionados durante pandemia do coronavírus tipo-2, máscaras cirúrgicas descartáveis, PFF2/N95, e máscaras domésticas em algodão. Análises realizadas em maio e junho de 2020, de acordo com norma ASTM D 737:2018. **Resultados:** realizados seis ensaios para dez unidades de cada máscara. LisLu20® (a) - duas camadas: 8,6 cm³/s/cm²; LisLu20® (b) - três camadas tipo asiática: 6,2 cm³/s/cm²; LisLu20® (c) - três camadas tipo PFF2/N95: 4,8 cm³/s/cm²; máscara cirúrgica descartável: 18,0 cm³/s/cm²; máscara PFF2/N95: 10,2 cm³/s/cm²; máscara de malha de algodão: 31,1 cm³/s/cm². **Conclusão:** máscaras LisLu20® realizaram barreira física e com método de prevenção/redução de riscos para infecções respiratórias. Produto doméstico, barato e sustentável, serviu de apoio emergencial complementar para reduzir os impactos da escassez de máscaras cirúrgicas descartáveis.
Descritores: Infecções por Coronavírus; COVID-19; Equipamento de Proteção Individual; Máscaras; Aprovisionamento.

RESUMEN
Objetivo: analizar la permeabilidad al aire de mascarillas desarrolladas para enfrentar emergencias biológicas. **Método:** estudio de laboratorio, con realización de pruebas a modelos de mascarillas de tela con inserción de elemento filtrante de celulosa (LisLu20®), fabricadas durante la pandemia de coronavirus tipo 2, mascarillas quirúrgicas desechables, PFF2/N95, y mascarillas domésticas de algodón. El análisis se realizó en mayo y junio de 2020, de acuerdo con la norma ASTM D 737:2018. **Resultados:** se realizaron seis ensayos con diez unidades de cada mascarilla. LisLu20® (a) - dos capas: 8,6 cm³/s/cm²; LisLu20® (b) - tres capas tipo asiática: 6,2 cm³/s/cm²; LisLu20® (c) - tres capas tipo PFF2/N95: 4,8 cm³/s/cm²; mascarilla quirúrgica desechable: 18,0 cm³/s/cm²; mascarilla PFF2/N95: 10,2 cm³/s/cm²; mascarilla de tela de algodón: 31,1 cm³/s/cm². **Conclusión:** Las mascarillas LisLu20® actuaron como barrera física y método para prevenir/reducir los riesgos de infecciones respiratorias. Es un producto doméstico, barato y sostenible, que sirvió como apoyo de emergencia complementario para reducir los impactos de la escasez de mascarillas quirúrgicas desechables.
Descriptores: Infecciones por Coronavirus; COVID-19; Equipo de Protección Personal; Máscaras; Aprovisionamiento.

INTRODUCTION

Since the initial identification of COVID-19 in China in December 2019, the global social landscape has been marked by complex and atypical circumstances, characterized by collective feelings of chaos, anxiety, fear, and uncertainty. These challenges were exacerbated by scientific and cultural limitations in understanding the clinical

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signs of the new disease, its symptoms, potential clinical and pharmacological treatments, availability of essential supplies, and emergency planning. This mobilization aimed to contain, mitigate, and safeguard public health, with the primary objective of halting the spread of that significant disease and, consequently, saving as many lives as possible—a central purpose of actions in the management of public health emergencies and disaster risks.

For professionals responsible for protective materials, debates around masks became a puzzle. The utility of masks should have been self-evident. Viruses like COVID-19 inhabit the respiratory tract[1] and are expelled into the air via droplets and aerosols during speaking, singing, coughing, or sneezing[2,3]. Masks made from various fabrics and fiber-based filters demonstrated varying efficiencies in blocking airborne droplets and aerosols[4].

This issue remains pertinent, and it is noteworthy that the Cochrane Library published an early update on physical interventions to control the spread of respiratory viruses, including the use of masks to contain the transmission of coronavirus and severe acute respiratory syndrome, even after the official declaration of the end of the pandemic.[5].

In Brazil, one of the countries most severely affected with the highest number of deaths, there was an abrupt disruption in the supply of material resources and a surge in the general population's consumption of hospital-grade masks at the beginning of 2020. This led to a significant increase in prices, resulting in shortages and even a lack of personal protective equipment (PPE).

In response, guided by World Health Organization (WHO) recommendations, Brazil's National Health Surveillance Agency (ANVISA) began advocating for non-professional cloth masks as a viable option to control pandemic spread[6]. Scientific evidence indicated a significant reduction in transmission rates when masks were used, offering useful policy implications despite the chaotic and rapidly changing scenario in terms of immunization and behavior[7].

Amid the shortage of PPE and its implications for the quality and safety of care in Brazilian healthcare facilities, members of the Teaching, Research, and Extension Group on Health in Emergencies and Disasters at the Federal University of Rio de Janeiro (GEPESED/UFRJ) conducted studies on potential technologies and emergency response strategies to address this biological disaster. Their efforts focused on developing health technologies aimed at improving logistics in emergency and disaster situations[8].

Thus, non-professional cloth masks gained not only epidemiological relevance but also popularity due to the authoritative statements from major sectors, agencies, and global organizations regarding their potential capacity to prevent or reduce the risk of COVID-19 transmission. Simultaneously, these guidelines helped alleviate the significant demand for medical-grade masks, which were primarily intended for healthcare professionals engaged in patient care in high-risk settings[9-11]. Therefore, the adoption of cloth masks emerged as a voluntary public health strategy at both national and international levels for the social control of SARS-CoV-2 and its variants[12].

From the onset of the COVID-19 pandemic, a global rush for protective masks led to their disappearance from store shelves. In response, Brazil's Ministry of Health began procuring large quantities of masks from domestic and international suppliers to ensure the protection of healthcare workers in medical facilities[13,14].

To guarantee the quality and safety of these personal protective equipment, air permeability tests were conducted to demonstrate filtration efficiency. Air permeability is understood to be directly related to a mask's ability to filter airborne particles. For this study, the cotton cloth used complied with the standards of the Brazilian Association of Technical Standards (ABNT) - Brazilian Standard (NBR) 14027/9[15].

The recommendations of the Health Ministry promoted the production of simple cloth mask models through a widespread public campaign aimed at mobilizing the population to use or make their own cloth masks. It was emphasized that, to serve as an effective physical barrier, homemade masks should meet specific criteria, including: having at least two layers of cloth (double-layered); being for individual use and not shared; using materials such as cotton, tricoline, non-woven cloth (TNT), or similar fabrics that completely cover the nose and mouth; and being properly sanitized and well-fitted to the face without gaps[16].

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The WHO and the Centers for Disease Control and Prevention (CDC) recommended cloth masks for the general population, advising that they be made with at least three layers to reduce the emission of particles into the environment when the mouth area is covered. Masks with multiple layers effectively blocked respiratory droplets ranging from 1-10 μm[17]. In this context, a cloth mask with lower air permeability may be more effective in filtering airborne viral particles, thereby reducing the risk of infection. Additionally, cloth masks with good air permeability protect both the wearer and those around them by preventing viral particles from entering the user's respiratory system and stopping the user from expelling viral particles into the environment, especially if they are infected and asymptomatic.

In response to this initial need to reduce risk, the GEPESED/UFRJ developed cloth masks by creating prototypes adapted to common facial shapes observed in the Brazilian population. A distinguishing feature was the inclusion of a cellulose-based filtering element to provide a potentially more effective physical barrier. Thus, the LisLu20® masks were produced with two or three layers of 100% cotton tricoline cloth, depending on the model. When the cellulose filtering element was included, an additional layer was added to the mask.

This study aimed to analyze the air permeability of masks developed for addressing biological emergencies and disasters. The study proposed cloth masks with more than two layers, differing from the initial recommendations by Brazil's Ministry of Health, which suggested cloth masks with only two layers and no filtering element, as outlined in Informative Note No. 3/2020-CGGAP/DESF/SAPS/MS, issued on April 2, 2020[16].

METHOD

This laboratory study involved developing three models of cloth masks, registered under the trademark LisLu20®, with the inclusion of a cellulose-based filtering element (coffee filter). To ensure the study's validity, measurable variables related to control strategies and effect observation were selected[8].

The research team included members of GEPESED/UFRJ and artisans who participated in designing, adjusting, and validating different models of 100% cotton tricoline cloth masks through preliminary domestic trials[7].

Three preliminary empirical tests were conducted, and their results were shared and disseminated via social media. The video is available in the following electronic address: https://youtu.be/vhoRRwB7pHA[8]. This operation motivated the second phase of the research, involving laboratory tests conducted in an ANVISA-certified facility[18].

Among the developed and tested models were: LisLu20® A: A 100% cotton tricoline cloth mask with a nasal clip, pleats, and two cloth layers, resembling surgical mask designs. It included a slit for inserting a filtering element as a third layer (Figure 1).

Figure 1: LisLu20® A cloth mask. Rio de Janeiro, RJ, Brazil, 2020.

LisLu20® B: Also made of 100% cotton tricoline, this mask featured a rectangular design without a nasal clip. This shape was widely used in Asia even before the COVID-19 pandemic It generally had three cloth layers,

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with the third layer serving as support for inserting a cellulose filtering element, forming a fourth layer (Figure 2).

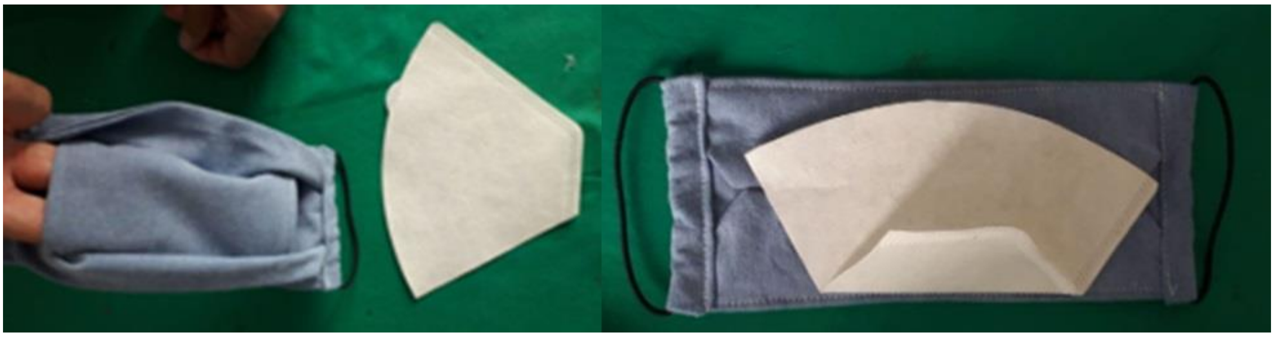

Figure 2: LisLu20® B cloth mask. Rio de Janeiro, RJ, Brazil, 2020.

LisLu20® C: A shell-shaped mask with a nasal clip, made of three layers of 100% cotton tricoline cloth. It resembled N95/PFF2 mask designs. In this model, the outermost cloth layer supported the insertion of a cellulose filtering element, resulting in four layers (Figure 3).

Figure 3: LisLu20® C cloth mask. Rio de Janeiro, RJ, Brazil, 2020.

The LisLu20® masks were designed to exceed the guidelines established by Brazil's Ministry of Health, as described in Informative Note No. 3/2020-CGGAP/DESF/SAPS/MS and Technical Note GVIMS/GGTES/ANVISA No. 4/2020. These notes aimed to provide guidance on producing cotton cloth masks for both the general population and healthcare services to support emergency COVID-19 prevention and control measures during the care of suspected or confirmed cases[10].

The laboratory research was conducted in two distinct phases. The first focused on identifying the most suitable test to validate the efficacy of cloth masks with a cellulose filtering element. In the second phase, a certified laboratory was selected to conduct the necessary tests[8]. After selecting the laboratory, the next step involved preparing an adequate number of mask samples for testing, following the institution's established criteria. In addition to the LisLu20® masks, disposable surgical masks, N95/PFF2 masks, and commercially available two-layer cotton cloth masks were included for comparison[8].

The selected laboratory provided guidance on determining the best test to compare the use of filtering elements in the three LisLu20® cloth mask models with commercially available masks. Such guidelines were provided by the Center for Technology in the Chemical and Textile Industry (CETIQT), a unit of the National Service

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for Industrial Training (SENAI), located in the state of Rio de Janeiro, Brazil. Due to the lack of specific guidelines for validating non-professional masks at that time, air permeability tests were suggested.

The selected laboratory belonged to REBLAS (Brazilian Network of Analytical Health Laboratories), a network of public and private units certified by ANVISA. The use of certified laboratories aimed to validate preliminary findings, which indicated that adding a cellulose filter to masks increased resistance to aerosol penetration[8] through empirical tests.

By late April 2020, the process of obtaining test reports began, with results signed via ICP-Brasil digital certification by an authorized laboratory signatory. The study's proposal was approved and registered under the signature of this article's first author.

For physical testing, ten units of each mask type were provided. The LisLu20® models followed uniform patterns to avoid potential alterations in results due to cloth pigmentation. The same quantity (ten units) was tested for other mask types. Additional documentation, such as CNPJ registration, company operating authorization (AFE), and ANVISA registration, was submitted for verification and compliance analysis.

All samples were labeled and accompanied by proposal numbers corresponding to test budgets, along with detailed descriptions of the tests. This information was provided through forms made available by the laboratory. The document also contained specific instructions for conducting physical tests on LisLu20® cloth masks with filtering elements, disposable surgical masks, industrialized N95/PFF2 masks intended for healthcare professionals, and then commercially available two-layer cotton cloth masks.

Therefore, the physical tests aimed to compare air permeability across these different mask types to provide safer decision-making guidance for health professionals, managers, and ordinary citizens. The tests were conducted according to ASTM D737:2018 standards established by ASTM International, which provide guidelines for determining airflow rates through porous materials[19].

Reports documenting test results provided detailed information on each mask type's air permeability, enabling clear comparisons between them.

Air permeability tests are commonly used to measure gas penetration capacity in polymeric materials such as films, coatings, and various fabrics, including non-woven fabrics (TNT), airbags, blankets, wool fabrics, knits, laminates, and pile fabrics. These materials may be untreated, heavily sized, coated, resin-treated, or treated with other substances[19].

Air permeability measures how easily gas particles pass through a material's physical structure. It is typically expressed as ventilation property, the amount of air passing through a unit area of cloth per unit time under specific pressure differences[19].

In this study, airflow rates were measured perpendicularly using 10 cm x 10 cm portions of each mask. Pressure drop and time readings were taken under specific air pressure differentials between the cloth's two surfaces. Testing conditions included temperature and humidity adjustments to ensure representative conditions aligned with industrial standards. No specific values were set; only physical barrier percentages were considered.

Testing involved securing cloth samples on an evaluation bench without edges or folds. Air permeability tests were then initiated by stabilizing differential pressure levels and recording results. Tests were repeated multiple times on different parts of each sample under consistent conditions. Air permeability was measured directly using laboratory instruments and expressed in SI units ($cm^3/s/cm^2$). Figure 4 shows the equipment used at SENAI/CETIQT's laboratory.

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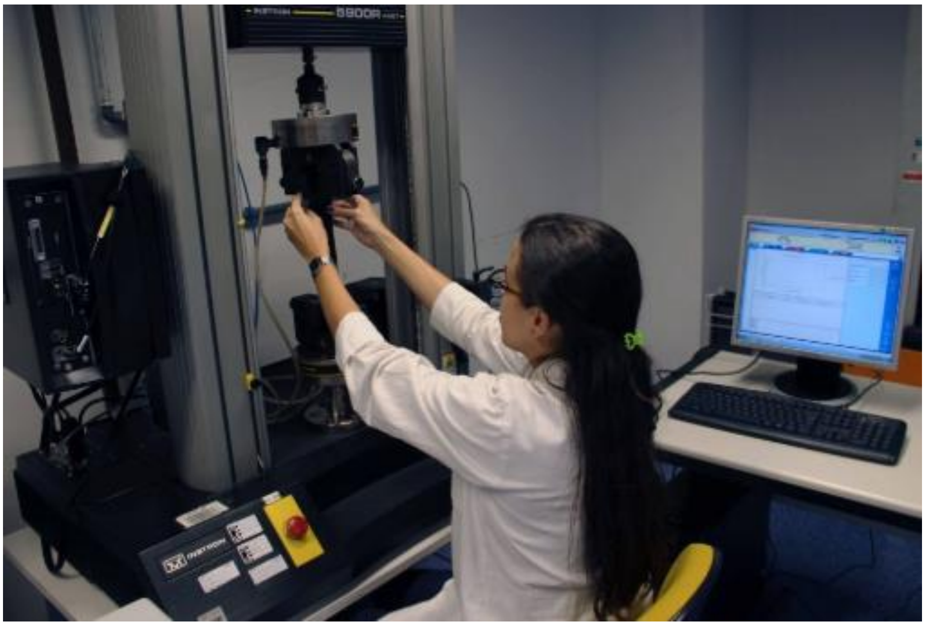

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Figure 4: Equipment for air permeability analysis. Rio de Janeiro, RJ, Brazil, 2020.

The budgeting and report issuance process took approximately 60 days, covering all study phases. The total cost for bench and air permeability tests was BRL 1,920.00. All samples were discarded after testing.

RESULTS

For air permeability analysis of LisLu20® cloth mask models alongside disposable surgical masks, industrialized N95/PFF2 masks, and two-layer cotton cloth masks, 60 units and 30 cellulose filters were used.

Results obtained from technical reports are presented in Table 1.

Table 1: Results of air permeability tests (ac) conducted at the SENAI/CETIQT laboratory – RJ – ASTM D737:2018 method. Rio de Janeiro, RJ, Brazil, 2020.

Type	Sample	Code and Date	Result (cm³/s/cm²)
Masks developed in the study (with cellulose filter)	Two-layer cloth mask LisLu20® A	1347/20-01 05/20/2020	8.6
	Three-layer cloth mask, Asian style LisLu20® B	1349/20-01 05/20/2020	6.2
	Three-layer cloth mask, N95-style (shell) LisLu20® C	1748/20-01 07/06/2020	4.8
Industrialized masks	Disposable surgical mask – health product	1353/20-01 05/20/2020	18.0
	N95/PFF2 mask – health product	1354/20-01 05/20/2020	10.2
	Two-layer cotton knit mask	1355/20-01 05/20/2020	31.1

Source: SENAI/CETIQT laboratory report. Rio de Janeiro, RJ, Brazil, 2020.

LisLu20® cloth masks demonstrated satisfactory results compared to physical barriers established by all tested masks. However, no laboratory-proposed scale was available as a parameter; only product comparability was assessed. Air permeability measurements were lower than industrialized masks.

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Cloth masks, with the addition of a cellulose filter element, demonstrate a capacity for physical barrier protection. This finding is supported by comparisons with industrially manufactured masks, which also feature a physical barrier composed of filters incorporated during their production process. Adding coffee filters reduced airflow speed due to cellulose weaves but maintained droplet-blocking efficacy.

In the evaluation of air permeability of masks made from two-layer cotton cloth without a filtering element, a higher air permeability value was observed, with a result of 31.1 $cm^3/s/cm^2$. This indicates that these masks allow air to pass through approximately six times faster than the LisLu20® C mask, which has an air permeability value of 4.8 $cm^3/s/cm^2$.

Industrialized professional-use masks showed higher permeability (18% $cm^3/s/cm^2$ and 10.2% $cm^3/s/cm^2$) compared to LisLu20® models with cellulose filters.

It can be inferred that, during the time experienced throughout the pandemic, LisLu20® masks could be used safely by society. Regarding the physical barrier through the air permeability test, it can be understood that industrially manufactured masks have superior technology, with other means in accordance with health product regulations that indicate their efficacy and protection.

DISCUSSION

From the onset of the abrupt disruption in the supply of masks for professional use and the chaotic scenario caused by the COVID-19 pandemic, researchers and health authorities worldwide began to establish guidelines for the main forms of protection, both for healthcare workers and for individuals with suspected clinical cases, including those diagnosed with the disease receiving home treatment[20]. As a result, there was a significant intensification in the use of PPE and the adherence to collective protective measures (CPM) as a means of controlling the spread of COVID-19[14].

WHO highlighted potential benefits of community use of homemade masks by healthy individuals to reduce exposure risks from asymptomatic or pre-symptomatic infected individuals[14]. Added to this is the concern regarding the conservation of cloth mask usage by the community to help reserve professional masks for frontline healthcare workers[21]. Considering the high transmissibility during the COVID-19 pandemic, the strategies adopted aimed to contain droplet spread and reduce the risks of respiratory infections in the general population.

As personal protective equipment, masks function as devices that typically act as physical barriers, reducing exposure and the risk of infection transmission. The protective effect of masks encompasses several factors, such as the potential to block droplet transmission, proper fit and reduced air leakage associated with mask use, adherence to usage, and proper disposal[10].

Experimental studies during the SARS outbreak in 2003 indicated that droplets from patients could reach a distance of approximately two meters from their source[12]. In this context, the adoption of mask use has been reiterated for the prevention of infectious agent transmission via droplets[21].

During the COVID-19 pandemic, the use of reusable cloth masks played a significant role, particularly for symptomatic individuals in home settings, caregivers, and people living in multi-occupant households. Additionally, these masks were employed in long-term care facilities for the elderly and in crowded environments, such as public transportation. In situations of scarcity, cloth masks were also used to meet the demand of healthcare professionals during the peak of virus dissemination.

Based on the analysis of conducted trials, the cloth masks developed through the doctoral thesis of the first author sought to help reduce exposure to biological agents[10]. The data obtained in this laboratory study corroborate their efficacy as physical barriers. It is believed that these protective devices, handcrafted according to the guidelines of health authorities in each country, may contribute in the future to preventing the transmission of diseases similar to COVID-19 within communities, aiming to reduce potential risks, especially in more vulnerable countries[10].

The construction and layering, as well as the cellulose-based filter element in the models presented in the study, demonstrated that the greater the number of layers, the more efficient the barrier provided. Moreover, the

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design of the LisLu20® C model, with its shell-like shape, ensures better sealing, resulting in lower air permeability, with a value of 4.8 cm³/s/cm².

The trial data showed that LisLu20® cloth masks with a cellulose filter element exhibited a lower level of air permeability compared to industrially produced cloth masks and cotton knit masks. This difference indicates their potential to protect and minimize risks. It is noteworthy that instructions on how to use, wash, reuse, and dispose of the filter element were compiled into a guide for all LisLu20® models[8,21].

The design of cloth masks plays a crucial role in their efficacy, particularly in terms of facial fit and comprehensive sealing. This is essential to ensure adequate protection, as highlighted in the scientific literature[20]. The filtration capacity of different fabrics varies widely, with 100% cotton fabrics demonstrating better performance as the preferred option. Cloth masks with two to three layers and a good fit around the face to prevent leakage are preferable models. This aligns with the results of the LisLu20®C mask trial, which achieved an air permeability of 4.8 cm³/s/cm². Cone-shaped or tetrahedral designs that allow for a snug fit to facial contours have demonstrated greater efficiency[22].

Regarding the number of layers, it was observed that barrier efficacy against permeability improves significantly with an increased number of cloth layers, closer weaving of 100% tricoline cotton fibers, and reduced pore size in these fibers. In other words, smaller pore sizes result in greater barrier capacity. Studies have suggested that fabrics composed of 100% cotton fibers are more recommended in this regard[23,24]. Cotton fibers are durable and possess properties that allow the skin to breathe, absorb moisture, and dry quickly. Additionally, longer fibers enhance cloth quality and durability.

This study aimed to highlight cloth masks while identifying potential improvements to prevent illness and minimize harm to workers involved in pandemic response efforts and society at large[25].

It is emphasized that, at the time of testing, there were no clear guidelines on how to produce cloth masks meeting well-established safety and effectiveness criteria. Comfort and usability must also be considered to ensure masks can be worn for extended periods, understanding that highly permeable masks may not provide adequate protection[26]. Conversely, overly restrictive masks may hinder breathing and cause discomfort. Another important consideration is public compliance and acceptance, which depends on measures taken by public health authorities to regulate mask use, thereby increasing population adherence to protective measures and consequently reducing virus spread.

Study limitations

As a limitation of the study, it is noted that other factors may influence the permeability of the tested masks. Further research is needed to explore the influence of factors such as moisture from exhalation, duration of use, frequency of replacement, and washing methods before disposal.

CONCLUSION

The study underscores the need for developing new health products and technologies in response to demands generated by public health emergencies and biological disasters, which involve seeking efficient alternatives to improve response standards, particularly in socioeconomically vulnerable countries and communities.

It was demonstrated that handcrafted cloth masks with cellulose filters, following health authority guidelines, played a role in preventing and reducing the risk of COVID-19 transmission. The LisLu20® mask, evaluated through air permeability trials, was validated as a promising option, particularly for citizens and high-risk groups, serving as a sustainable alternative due to its materials.

Looking ahead, it is recommended to consider the use of cloth masks with cellulose filter elements by the population during biological events requiring social distancing, including by healthcare professionals and specific groups during pandemics. However, further research is necessary to expand understanding of the efficacy of this alternative type of personal protective equipment, as well as cost-effectiveness analyses.

Finally, it is emphasized that the proposal for cloth masks reflected the impacts of the COVID-19 pandemic, a global phenomenon marked by a sudden disruption in the supply of certified personal protective equipment, which intensified the debate on more effective risk management strategies for public health emergencies and biological disasters.

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Conceptualization, L.R.R., A.J.R.R.S.C., A.W., S.K., M.R.B. and A.B.O.; methodology, L.R.R. and A.B.O.; validation, L.R.R. and A.B.O.; formal analysis, A.B.O.; investigation, L.R.R., A.J.R.R.S.C., A.W., S.K., M.R.B. and A.B.O.; resources, L.R.R.; data curation, L.R.R.; manuscript writing, L.R.R.; writing – review and editing, L.R.R., A.J.R.R.S.C., A.W, S.K., M.R.B. and A.B.O.; visualization, A.B.O.; supervision, A.B.O.; project administration, L.R.R. All authors read and agreed with the published version of the manuscript.