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Mitigation of microfibers release from disposable masks – An analysis of structural properties

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ABSTRACT

The use of disposable face masks increased rapidly among the general public to control the COVID-19 spread. Eventually, it increased the disposal of masks and their associated impacts on environmental pollution. Hence, this study aims to analyze the impact of nonwoven fabric structural parameters and weathering on the microfiber release characteristics. Spunbond polypropylene nonwoven with four different weights and meltblown nonwoven with two different weights were used in this study to analyze microfiber release at dry, and wet conditions to simulate improper disposal in the environment. Exposure to sunlight significantly increases the microfiber release from 35 to 50% for spunbond fabric and 56–89% for meltblown fabric. Weathering in sunlight structurally affected the tensile properties of the polypropylene fibers due to photodegradation. The study showed that each mask can produce $1.5 \times 10^2$ and $3.45 \times 10^3$ mg of microfiber/mask respectively in dry and wet states. In the case of structural parameters, a higher GSM (grams per square meter), abrasion resistance, bursting strength, and thickness showed a positive correlation with microfiber release in both fabrics. Significantly a higher microfiber release was reported with meltblown fabric than the spunbond for a given GSM. The presence of finer fibers and more fibers per unit area in meltblown fabric was noted as the main cause. Nonwoven fabric GSM and the number of fibers in a specific area showed a higher influence on microfiber release. Based on the mask consumption reported in the literature, India alone can produce around $4.27 \times 10^2$ tons of microfibers/week as an average of dry and wet conditions. The study suggests that the proper selection of physical parameters can significantly reduce the microfiber fiber release at all stages.

1. Introduction

COVID – 19 (Corona Virus) pandemic’s impact on humanity is irreversible. Until the beginning of 2021, no proper vaccines were invented, and hence, to protect from this airborne COVID-19 spread, the World Health Organization (WHO) mandated the use of masks (WHO, 2022). The use of personal protective equipment (PPE) increased multi-fold among medical practitioners and also among the general public due to the wide-spreading nature of the infection (WHO, 2020a). Use of masks, maintaining social distancing in public places, and washing or sanitizing the hands frequently are vital practices adapted to control the spread of COVID-19 (CDC, 2022). The recent variant that was identified at the end of December 2021 is Omicron, which is one of the fast-spreading variants among the COVID – 19 viruses (WHO, 2021). To control the infection, in January 2022, again several nations imposed a lockdown.

To date, the use of masks in public places to control the spread of the COVID-19 virus is mandated in several countries. During the pandemic, several types of masks were in use, among that disposable or tri-layered surgical masks are the common type that is widely adopted due to their cheaper price and higher filtration efficiency against droplets (Connor, 2021). The disposable nonwovens are made of polypropylene (PP) and higher density polyethylene (HDPE) using either spun bonding or meltblown process (Chua et al., 2020). A typical disposable mask consists of three layers, in which top and bottom layers are made of PP and HDPE blended spunbond nonwoven, and the middle layer is made of pure PP meltblown nonwoven (Henneberry, 2021).

When the use of masks is mandated, a sudden increase in consumption and disposal was noted all over the world. WHO estimated that in 2020, health care workers alone required 89 million medical masks, 76 million gloves, and 1.6 million goggles per month (WHO, 2020b). Similarly, if we consider countries with huge populations like...
China and India, a huge quantity of masks was used per day. Hence, improper disposal of these COVID-19 litters will lead to a huge dump on the environment. This issue was recently addressed by several researchers by measuring the mask litter on the streets, beaches, public places, and freshwater systems (Ammendolia, 2021; Cordova et al., 2020; De-la-torre, 2020; Fadare and Elvis, 2020; Kutralam et al., 2020; Okuku et al., 2020; Zambrano-monserrate, Alejandra, and Sanchez-alcalde 2020). Exposure to sunlight, wind, water, and other environmental factors degrade and disintegrate the textile fibers in the masks disposed of. Such degraded fibers are released into the atmosphere, land, and water sources as micro-sized debris that are classified as microplastic based on its size. Microplastics are generally tiny particles that are smaller in size, typically less than 5 mm (or sometimes 1 mm) (Browne et al., 2008), and released into the environment either directly as small particles (primary microplastics) or by the degradation of plastic materials (secondary microplastics) (Boucher and Friot, 2017). Due to the increased use and improper disposal of COVID-19 masks, it can act as a source of microfiber (a type of microplastic that originates mainly from textiles) emission into the environment. Several researchers reported microfibers as a dominant shape that was found in the environment under the microplastic categories (Browne et al., 2011; Napper and Thompson, 2016).

Production, use, and laundering of synthetic textiles are reported as the major sources of microfiber emission into the environment (Belzagi et al., 2017; Carney Almroth et al., 2018; De Falco et al., 2019; Napper and Thompson, 2016; O’Brien et al., 2020; Zambrano et al., 2019). Several researchers reported the impact of microfiber on the marine system (Gago et al., 2018), terrestrial environment (de Souza Machado et al., 2018), atmospheric pollution (Liu et al., 2019), and also the health impact on aquatic animals (Rebelein et al., 2021) and humans (Blackburn and Green, 2021). A survey conducted from September 2019 to October 2020 showcased a sudden increment of 84% in mask consumption during the pandemic (Roberts et al., 2021). Similarly, after 100 days of the pandemic, a 54% increment in the COVID litter was reported in Kenyan rivers and beaches (Okuku et al., 2020). The multifold increment in the use of disposable masks plays a crucial role in microfiber pollution. They are also added to this category of pollution as microplastics per mask in 24 h. Though huge variation was reported among single layers, a large number of microfibers were released from the top and bottom layers than the middle layer. The lower microfiber release may be due to the insufficient supply in different countries during the pandemic. The study also evaluated the effect of natural weathering (2 months) on the microfiber release. The results showed that 24 h immersion of masks may release 3,600, 5,400, and 4,400 microfibers respectively for water, detergent, and alcohol. When three washes were done repeatedly, the release amount increased to 5.59 × 10^4, 8.8 × 10^4, and 7.68 × 10^4 microfibers respectively for water, detergent, and alcohol. In terms of mass, masks lose 0.47%, 1.14%, and 0.85% of weight after treatment. In the case of the weathering process, an increment of 2.5 × 10^4 times was noted with the mask and it can release up to 6.4 × 10^8 microfibers. The study confirmed that the aged masks can release a large number of microfibers into the environment than the unused new masks (Shen et al., 2021). Similar research reported the effect of new and used masks on microfiber release that are sourced from 18 different brands. The results of the study showcased that all the masks will shed microfibers while immersed in water. The new masks released 1.83 × 10^2 ± 78.4 microplastics and the used mask released 1.25 × 10^4 ± 403.5 microplastics per mask in 24 h. Though huge variation was reported among the masks, 70% of the microplastics noted are microfibers. As the study measured the microfiber release in the mask without separating the individual layers, a large number of microfibers were released from the top and bottom layers than the middle layer. The lower microfiber release from the inner layer may also be due to their different manufacturing technology (meltsblown) than the outer layer (spunbond). As a whole, the study predicted that in 2020, China alone produced 100 billion face masks and they can potentially release 1.2 × 10^14 seawater. However, a higher amount of release from those masks was reported after 24 h of the UV weathering process. The mask treated with seawater after weathering can shed approximately 1.73 × 10^2 microfibers/mask. Weathering process significantly increased the microfiber release and a lot of fiber aggregates were noted in the surface water. FTIR analysis performed on the weathered mask confirmed the degradation of the fibers due to the oxidation process. The microscopic level changes in the molecular structure of the polypropylene fibers like free radical generation cause chain cleavages in the backbone and reduce the strength. Further to the chemical degradation, the mechanical abrasion developed in the seawater due to other sediments and fragments also causes mechanical degradation in the mask. The study reported a mass loss of 0.2% on the mask after the degradation, which in turn, resembles the release of microfibers when exposed to a real-time situation. The need for long-time evaluation to understand the real-life impact was insisted upon. However, based on the global mask production in 2020, a study reported that 7.2 × 10^3–3.12 × 10^4 tons of microplastics will accumulate in the marine environment (Saliu et al., 2021). A study investigated the microfiber releasing capacity of two-layer masks made of synthetic fibers. Researchers stirred the reusable mask in a glass beaker with ultrapure water, detergent, and alcohol for 24 h and evaluated microfiber release (Shen et al., 2021).

Recently few researchers experimented and measured the potential of these improperly disposed masks to release microfibers. Researchers used seven different branded masks and evaluated their microfiber release characteristics against artificial UV weathering and artificial seawater weathering processes. The results of the study showed a release of 398 ± 46 microfibers/masks (average of seven brands) in artificial seawater. However, a higher amount of release from those masks was reported after 24 h of the UV weathering process. The mask treated with seawater after weathering can shed approximately 1.73 × 10^2 microfibers/mask. Weathering process significantly increased the microfiber release and a lot of fiber aggregates were noted in the surface water. FTIR analysis performed on the weathered mask confirmed the degradation of the fibers due to the oxidation process. The microscopic level changes in the molecular structure of the polypropylene fibers like free radical generation cause chain cleavages in the backbone and reduce the strength. Further to the chemical degradation, the mechanical abrasion developed in the seawater due to other sediments and fragments also causes mechanical degradation in the mask. The study reported a mass loss of 0.2% on the mask after the degradation, which in turn, resembles the release of microfibers when exposed to a real-time situation. The need for long-time evaluation to understand the real-life impact was insisted upon. However, based on the global mask production in 2020, a study reported that 7.2 × 10^3–3.12 × 10^4 tons of microplastics will accumulate in the marine environment (Saliu et al., 2021). A study investigated the microfiber releasing capacity of two-layer masks made of synthetic fibers. Researchers stirred the reusable mask in a glass beaker with ultrapure water, detergent, and alcohol for 24 h and evaluated microfiber release (Shen et al., 2021).

The study proposed that the washing of masks may be necessary due to the insufficient supply in different countries during the pandemic. The study also evaluated the effect of natural weathering (2 months) on the microfiber release. The results showed that 24 h immersion of mask may release 3,600, 5,400, and 4,400 microfibers respectively for water, detergent, and alcohol. When three washes were done repeatedly, the release amount increased to 5.59 × 10^4, 8.8 × 10^4, and 7.68 × 10^4 microfibers respectively for water, detergent, and alcohol. In terms of mass, masks lose 0.47%, 1.14%, and 0.85% of weight after treatment. In the case of the weathering process, an increment of 2.5 × 10^4 times was noted with the mask and it can release up to 6.4 × 10^8 microfibers. The study confirmed that the aged masks can release a large number of microfibers into the environment than the unused new masks (Shen et al., 2021). Similar research reported the effect of new and used masks on microfiber release that are sourced from 18 different brands. The results of the study showcased that all the masks will shed microfibers while immersed in water. The new masks released 1.83 × 10^2 ± 78.4 microplastics and the used mask released 1.25 × 10^4 ± 403.5 microplastics per mask in 24 h. Though huge variation was reported among the masks, 70% of the microplastics noted are microfibers. As the study measured the microfiber release in the mask without separating the individual layers, a large number of microfibers were released from the top and bottom layers than the middle layer. The lower microfiber release from the inner layer may also be due to their different manufacturing technology (meltsblown) than the outer layer (spunbond). As a whole, the study predicted that in 2020, China alone produced 100 billion face masks and they can potentially release 1.2 × 10^14

| Abbreviations: | Microplastics Plastic particles less than 5 mm in size | Microfibers Fibrous particles less than 5 mm in size |
|---------------|---------------------------------|---------------------------------|
| GSM           | Grams per Square Meter         | S                               |
| COVID         | Corona Virus Disease           | Number of 2 × 2 mm squares in the filter paper that effectively have fibers |
| WHO           | World Health Organisation      | F                               |
| PPE           | Personal Protective Equipment   | Number of fibers in one 2 × 2 mm square |
| PP            | Polypropylene                  | N                               |
| HDPE          | High Density Polyethylene      | Number of fibers in one filter paper |
| UV            | Ultraviolet                    | n                               |
| FTIR          | Fourier Transform Infrared     | Number of fibers released per sq.cm of fabric |
| ANOVA         | Analysis of Variance           | V                               |
| SDG           | Sustainable Development Goals   | D                               |
| UN            | United Nations                 | M                               |
|               |                                 | Mass of fibers in one filter paper |
|               |                                 | m                               |
|               |                                 | Mass of fibers released per sq.m of fabric |
|               |                                 | r                               |
|               |                                 | p                               |
|               |                                 | Mass of fibers released per sq.m of fabric |
|               |                                 | Pearson Coefficient             |
|               |                                 | Correlation Coefficient         |

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microplastics into the environment within 24 h of disposal (Chen et al., 2021).

The effect of shoreline disposal of tri-layer masks was analyzed and reported by Wang et al. (2021). The study analyzed the microfiber release from the mask after a different duration of UV weathering. The results of the research reported a higher shedding of microfiber from all the layers of the mask while increasing the duration of weathering. However, the middle layer of the mask got affected by both physical and chemical damage due to UV exposure. Likewise, the surface roughness and water contact angle of the top and bottom layers of the mask got altered after weathering process. Research work reported a release of $4.84 \times 10^5$ microplastics from the new virgin mask and the quantity increased to $1.57 \times 10^6$ microplastics from the weathered mask (Wang et al., 2021). Similarly, when the masks were analyzed in presence of sand to simulate the shoreline situation, researchers found that a single weathered mask can release up to $1.6 \times 10^7$ microplastic in 24 h.

Table 1
Summary of literature that reported the microfiber pollution from disposable tri-layer masks and the research gap identified.

| S. No | Reference | Materials evaluated | Experimental Procedure | Microfiber Quantification and Characterisation methods | Parameters evaluated |
|-------|-----------|---------------------|------------------------|--------------------------------------------------------|----------------------|
| 1     | Sullivan et al. (2021) | Disposable plastic face mask | Microfiber release - Masks were immersed in DI water for 4 h with intermittent stirring | SEM – EDX, Light Microscopy, LC-MS | Potential of masks to release microfibers, Leachable metals and organic compounds |
| 2     | Wang et al. (2021) | Disposable tri-layer mask | Weathering simulation – Individual layers of the masks are exposed to UV irradiation for different periods; Microfiber release - Masks are immersed in DI water for 24 h with the agitation of 300 rpm in the presence and absence of sand. | FTIR analysis, AFM analysis, Laser in-situ scattering and transmissometry analyzer | Physico-chemical change in the mask structure with exposure to UV irradiation, Microfiber release of the weathered masks in an aqueous environment |
| 3     | Shen et al. (2021) | Disposable surgical mask | Weathering simulation – Natural weathering by placing the masks in the terrace of the building for 2 months; Microfiber release - Masks were immersed in different mediums (water, detergent solution, alcohol) for 24 h with an agitation of 120 rpm. | Electron microscope, FTIR analysis, ImageJ software | Effect of physical abrasion due to sand on microfiber release, Effect of natural weathering, Effect of individual layers, Effect of different exposure mediums (water, detergent, alcohol) |
| 4     | Salio et al. (2021) | Surgical mask | Aging simulation – Masks are exposed to UV radiation for 180 h; Microfiber release - Masks are immersed in artificial seawater for 24 h with an agitation of 4000 rpm. | SEM, Micro-FITR | Microfiber release of masks exposed to the marine environment, Comparison of a naturally weathered mask with experimentally weathered masks. |
| 5     | (Morgana et al., 2021) | Tri-layer surgical face mask | Microfiber release - Masks are immersed in MilliQ water and subjected to different shear forces by means of varying the energy density and time of exposure. | Optical stereomicroscope, LED fluorescence microscope, CytoScope HP | Effect of different levels of mechanical stress on the release of micro- and nano-particles. |
| 6     | (Ma et al., 2021) | Face masks | Microfiber release – Whole masks were put into a glass beaker with MilliQ water and shaken vigorously for 3 min. | SEM, AFM, FTIR | Release of micro- and nano-particles from face masks, Contamination level of nasal mucus of the mask wearer. |
| 7     | Chen et al. (2021) | Surgical Disposable face mask, N-95 respirator, Normal disposable mask | Replication of used mask - Mask is worn for one day; Microfiber release - Masks are immersed in DI water for 24 h with the agitation of 120 rpm. | Stereomicroscope | Effect of usage on microfiber release, Effect of different types of masks |
| 8     | Rathinamoorthy and Raja Balasaraswathi (2022) | Tri-layer disposable nonwoven face mask | Weathering simulation – Natural weathering by placing the masks on the terrace of the building for 30 days; Microfiber release - Masks were rubbed in a dry state; soaked in tap water and seawater for 10 h; soaked and rubbed in tap water and seawater for 15 min. | FTIR, Digital Microscope | Effect of natural weathering, Effect of wet and dry states of exposure, Effect of seawater and freshwater |
| 9     | De Felice et al. (2022) | Reusable and re-washable face masks, Disposable face masks | Microfiber release – Masks were laundered in the washing machine (800 rpm, 1:19 h, 30°C) | SEM, FTIR, Stereomicroscope | Effect of fiber compositions of reusable masks on microfiber release during laundering, Effect of types of masks, Effect of individual layers, Effect of environmental conditions (water, sediment) |
| 10    | Wu et al. (2022) | Common mask, Surgical mask, Face filtering piece mask | Microfiber release – Masks were put in tubes having DI water and sediments and rotated at 60 rpm. | SEM, Fluorescence microscopy, Laser scanning microscope | Effect of types of masks, Relationship between mask mass and microfiber release, Release kinetics of microfibers, The potential release of micro and nano-particles, Leachable organic compounds in the masks |
| 11    | Liang et al. (2022) | N-95 masks, Medical-surgical masks, Normal medical masks | Microfiber release – Masks are immersed in DI water for 24 h with the agitation of 220 rpm | Optical Microscope, SEM, Raman Spectroscopy | |
| 12    | Delgado-Gallardo et al. (2022) | Medical grade Disposable Plastic face masks (FFP-2 and IIR) | Microfiber release - Masks were immersed in DI water for 4 h and stirred gently once an hour. | Field Emission gun scanning electron microscope (FEG-SEM), Liquid Chromatography-Mass Spectroscopy | |
exposure. Around $4.7 \times 10^3$ to $24.6 \times 10^3$ microplastics will be released into the breathing environment (Wang et al., 2021). Most recently, another study analyzed the microfiber release from the disposable masks, as well as the individual layers under different exposure conditions including freshwater, seawater, dry abrasion, and natural weathering. The study reported a higher number of microfiber releases in the dry state, which is followed by seawater and freshwater. The higher fuzz formation in the dry state has been noted as the major reason for the higher release of microfibers. In addition, the change in the density and pH of the seawater resulted in a higher release than that of freshwater (Rathinamoorthy and Raja Balasaraswathi, 2022).

As reported by the previous researchers (Shen et al., 2021), weathering of masks increased their microfiber release potential (Rathinamoorthy and Raja Balasaraswathi, 2022). Table 1 consolidates the existing research work in this domain and showcases the necessity of the current study. It can be also noted from Table 1 that none of the studies reported the effect of structural properties of the mask on its microfiber release behaviour.

Results from literature exhibited a higher vulnerability of the different layers of the masks when exposed to artificial or natural weathering. Similarly, treatment with UV light degraded the middle layer of the mask significantly. The existing studies mainly focused on the effect of the external environment to which the masks are exposed during usage and after disposal. However, the inherent fabric properties of the nonwovens such as the production method, and structural parameters were not evaluated as mentioned in Table 1. As the weathering process directly damages the physical structure of the nonwoven, the changes in the structural parameter are one of the important elements that can affect the microfiber release. A clear understanding of the effect of fabric properties can potentially help in the identification of potential solutions for the issue at the production stage which will be a controllable parameter whereas the external factors are uncontrollable. Hence, in this study, both spunbond and meltblown nonwoven polypropylene structures with different grams per square meter (GSM) were analyzed under both dry and wet conditions. The results were correlated with the physical and chemical characteristics of concerned nonwoven fabrics.

2. Materials and methods

The nonwoven fabric samples were sourced and their microfiber release potentials under different conditions were examined. The quantification of microfiber release was made and the data is analyzed statistically for their relationship. The methodology flow chart is shown in Fig. 1.

2.1. Non-woven fabric samples

Polypropylene nonwoven fabrics made of spunbond and meltblown techniques were sourced from PSG College of Technology, Centre of Excellence for Industrial Textile and Home Textile, Coimbatore, India. The selected fiber composition and grams per square meter (GSM) of the sourced fabrics are the most commercially used in disposable masks. Table 2 summarises the fabric specifications of the samples analyzed.

2.2. Natural weathering

The non-woven fabrics were exposed to natural weathering which can resemble the effect of environmental conditions to which the masks will be exposed when they are disposed. To understand the effect of weathering on spunbond and meltblown fabrics, weathering has been made as reported in the previous studies (Rathinamoorthy and Raja Balasaraswathi, 2022; Wang et al., 2021). Both the samples (spunbond & meltblown) of the same weight (25 g/sq.m) were exposed to natural weathering for 30 days (9th January 2022 – 9th February 2022) on the terrace of a building of the institute (Average temperature – 25 °C; Average humidity – 71%; UV index – 6; Precipitation – 8 mm).

2.3. Microfiber release analysis

Microfiber release of new fabrics and weathered fabrics were carried out under three different conditions (Rubbing in the dry state, Rubbing in the wet state, and Soaking in water without agitation). Distilled water is preferred to avoid the cross-contamination of microfibers in the water.

Table 2

| Sample | Fabric Type | Fiber Composition | Fabric weight/GSM (grams/sq. m) |
|--------|-------------|-------------------|---------------------------------|
| S15    | Spunbond    | 100% Polypropylene| 15                              |
| S20    | Spunbond    | 100% Polypropylene| 20                              |
| S25    | Spunbond    | 100% Polypropylene| 25                              |
| S30    | Spunbond    | 100% Polypropylene| 30                              |
| M25    | Meltblown   | 100% Polypropylene| 25                              |
| M30    | Meltblown   | 100% Polypropylene| 30                              |

Fig. 1. The methodology adopted for the microfiber analysis from disposable tri-layer masks.
i. Rubbing in the dry state – The sample is folded and rubbed against itself 120 times (60 – face to face; 60 – back to back) inside a sealed container to simulate the wear time abrasions. The inner surface of the container is lined with filter paper to collect the fibers released during the process.

ii. Rubbing in the wet state – The sample is immersed in distilled water (150 mL) and rubbed and beaten with a plastic rod continuously for 15 min while immersed in water. Then the water is filtered using Whatman Grade 1 filter paper (Pore size: 11 μm)

iii. Soaking in water – The sample is immersed in distilled water (150 mL) and kept idle for 10 h. Then the water is filtered using Whatman Grade 1 filter paper (Pore size: 11 μm). These two methods were adopted to showcase the microfiber shedding capacity of disposed masks

The fabrics sourced were directly analyzed and the sample size was kept as 10 cm × 10 cm. Each experiment has been replicated three times.

2.4. Microfiber quantification method

For each experiment, the microfibers were collected using a filter paper and analyzed with the help of a 1000 X Digital Light Microscope (LaboMed Lx 300). The microscopic view of the fibers in the filter paper is shown in Fig. 2. ImageJ software has been used for the analysis of microscopic images. Microfiber release has been quantified in terms of both counts (number of fibers) and weight (mass of fibers).

2.5. Microfiber count (number of fibers)

For quantifying the microfibers in the filter papers, filter paper was gridded by 2 × 2 mm squares. 30 squares along the diagonal of the filter paper are chosen and the number of fibers in each square was counted manually and the average number of fibers in one square was calculated. Based on the number of squares (S) effectively having fibers and the average number of fibers (F) in one square, the total number of fibers in the filter paper was calculated using equation (1). Based on the sample size, the number of fibers released from 1 square centimeter of the fabric has been calculated using equation (2) (De Falco et al., 2018; Napper and Thompson, 2016).

Number of fibers in filter paper, \( N = S \times F \)  

Number of fibers released/ sq.cm of fabric, \( n = \frac{N}{100} \)  

2.6. Microfiber weight

Based on the number of fibers released, the mass of the fibers has been estimated. Assuming fibers as cylinders, the volume (V) and density (D) of fibers have been used to estimate the mass. Equations (3) and (4) have been used to estimate the mass of fibers in one filter paper and the mass of fibers released per sq. meter of fabric respectively.

Mass of fibers in filter paper, \( M = N \times V \times D \)
Mass (mg) of fibers released/ sq.m of fabric, $m = M \times 100$ (4)

2.7. Quality Assurance

To avoid contamination due to other particles, the tools and materials that are used in the experiment were washed with ultrapure water. Air filters were used in the work area to avoid contamination due to airborne microplastics. Black coats and particle-free nitrile gloves were worn during the experimentation process to differentiate the fibers released from the clothes of the analysts.

2.8. Analysis of structural and physical properties

Structural and physical properties such as thickness, filament diameter, abrasion resistance, and bursting strength of the non-woven samples were analyzed. The thickness of the fabric sample was analyzed as per the standard ASTM D 1777-96 whereas the filament diameter was measured from the microscopic image of the fabrics. Abrasion resistance and bursting strength of the fabrics were tested using ASTM D 4966 and ASTM D 3786 standards respectively.

2.9. FT-IR analysis

To analyze the chemical changes in the weathered and unweathered samples, FT-IR analysis has been performed. The testing method which is used for FT-IR analysis was KBr plate method. The FT-IR spectrum is measured at the resolution of 1.00/cm with wave numbers from 4000 to 400/cm.

2.10. Statistical analysis

The significance of the variation of microfiber release from the nonwoven fabrics was analyzed with one-way ANOVA. For understanding the relationship between the parameters, correlation coefficient ($r$) has been used. All the statistical analyses are done using Microsoft Excel and Origin 2019b Software.

3. Results and discussion

The microfiber release from different nonwoven fabrics under different conditions has been experimented and the quantified microfiber release for the specified experiment is provided in Table 3. In this study, the nonwoven fabrics made of spunbond and meltblown methods with different grams per square meter were analyzed. Despite the higher microfiber release from all the selected nonwoven fabrics, variations can be noted based on the nature of samples, weathering duration, and exposure conditions. A control sample was included in this study to measure the atmospheric and other possible microfiber contamination. The results reported in Table 3, showed an insignificant level of contamination from the external sources. A quantity of 2.20 ± 1.48 microfibers per filter paper (122.71 sq.cm) was identified in the control sample of three replicates. The colour of the fibers in the blank sample was black which confirmed that these fibers are released from the lab coats. Being small in quantity and easily differentiable from the fibers released from masks (white and blue colour), during the analysis of the results, the impact of atmospheric and other sources of contamination was neglected.

3.1. Effect of external conditions on different samples

In this study, selected nonwoven samples were exposed to different conditions to simulate the weathering of masks when they are improperly disposed of in the terrestrial environment or aquatic environment. The non-woven samples which are exposed to natural weathering were noted to release significantly higher microfibers (35.9–89.7%)

| Experiment | Sample | Weathing Duration | Condition | Microfiber count (fibers/sq. cm) | Microfiber mass (mg/sq.m) |
|------------|--------|-------------------|-----------|---------------------------------|--------------------------|
| 1          | S15    | Rubbing in dry state | 296.82 ± 40.25 | 1145.90 ± 168.85 |
| 2          | S15    | Rubbing in wet state | 102.32 ± 13.24 | 318.78 ± 10.38 |
| 3          | S15    | Soaking in water | 45.13 ± 0.68 | 178.14 ± 54.99 |
| 4          | S20    | Rubbing in dry state | 658.92 ± 69.31 | 1502.32 ± 34.29 |
| 5          | S20    | Rubbing in wet state | 90.73 ± 3.03 | 263.28 ± 30.36 |
| 6          | S20    | Soaking in water | 37.36 ± 0.76 | 123.09 ± 6.58 |
| 7          | S25    | Rubbing in dry state | 782.21 ± 135.85 | 1867.47 ± 566.56 |
| 8          | S25    | Rubbing in wet state | 102.75 ± 9.61 | 606.87 ± 111.73 |
| 9          | S25    | Soaking in water | 61.13 ± 1.21 | 483.14 ± 49.73 |
| 10         | S30    | Rubbing in dry state | 773.21 ± 137.95 | 1907.39 ± 178.89 |
| 11         | S30    | Rubbing in wet state | 333.19 ± 9.26 | 1043.01 ± 133.95 |
| 12         | S30    | Soaking in water | 92.78 ± 11.33 | 301.80 ± 84.53 |
| 13         | M25    | Rubbing in dry state | 898.17 ± 14.43 | 2459.23 ± 378.12 |
| 14         | M25    | Rubbing in wet state | 175.27 ± 2.67 | 878.98 ± 31.47 |
| 15         | M25    | Soaking in water | 32.03 ± 4.96 | 215.60 ± 21.05 |
| 16         | M30    | Rubbing in dry state | 1347.16 ± 113.55 | 4113.57 ± 469.74 |
| 17         | M30    | Rubbing in wet state | 139.56 ± 14.56 | 464.42 ± 106.40 |
| 18         | M30    | Soaking in water | 105.98 ± 6.94 | 402.12 ± 42.82 |
| 19         | S25    | 30 days | 1219.69 ± 216.43 | 4107.78 ± 598.83 |
| 20         | S25    | 30 days | 178.02 ± 14.81 | 878.12 ± 256.65 |
| 21         | S25    | 30 days | 123.38 ± 28.14 | 480.57 ± 22.28 |
| 22         | M25    | 30 days | 2061.03 ± 366.28 | 9639.00 ± 2309.01 |
| 23         | M25    | 30 days | 852.97 ± 50.45 | 5294.84 ± 921.16 |
| 24         | M25    | 30 days | 312.15 ± 187.20 | 2052.25 ± 1733.55 |
| Blank      | B1     | Control sample | 2.20 ± 1.48 | 2.20 ± .*

*a As fiber density and fiber type are not known the mass of the fibers from the blank sample was not evaluated.
increment) in all the cases (different samples, different experimental conditions) than the unweathered samples. This increment is due to physical changes like fiber breakage or deterioration in the fabric structure under exposure to the environment (Rathinamoorthy and Raja Balasaraswathi, 2022). Though the microfiber release was found to get increased with weathering, the level of increment varies with the textile material properties. Fig. 3 shows the difference in the increment percentage of microfibers released from spunbond and meltblown samples of similar weight. In the case of spunbond samples, the microfiber release was increased by an average of 42.9 ± 7.3% under different experimental conditions whereas meltblown samples showed 75.2 ± 17.1% increment after natural weathering. This shows that the effect of natural weathering will be different for different fabrics. Based on the results, it can be noted that the meltblown
fabrics (intermediate layers of tri-layer masks) are more prone to get damaged than the spunbond fabrics. This was in line with the previous research in which the researcher reported higher microfiber release from the middle layer (meltblown layer) of a disposable mask after UV weathering (Wang et al., 2021). To confirm this phenomenon, structural changes in both spunbond and meltblown fabrics were analyzed under a microscope. Fig. 4 shows the microscopic view of meltblown and spunbond samples before and after weathering. Severe damage to the structure and fiber breakage on weathered spunbond and meltblown fabrics are clearly evident (arrow marks). The fibers which are used in the meltblown fabrics were finer than that of spunbond fabrics, which was evident in Fig. 4 (Table 3). This could also be the potential reason for higher damage to meltblown fabrics than spunbond fabric when exposed to natural weathering. The same reason can also be mentioned for the higher number of fiber shedding from the meltblown fabric. Smaller fiber size and more number of fibers per unit area in meltblown fabrics compared to the spunbond fabric are the main reasons for higher microfiber release from meltblown fabrics.

The fiber damages and increased microfiber release characteristics of the weathered masks are highly related to the photodegradation effect of both spunbond and meltblown fabrics. Polypropylene fibers are known for their low photo-oxidative stability for sunlight and air (Almond, 2020). During the weathering process, the UV rays from the sunlight interact with the polypropylene surface and create exciting chromophores on the surface. These exciting chromophores promote degradation in the presence of sunlight and damage the material structure. The free radicals developed in this process cause cleavages and crosslinking reactions in the backbones and degrades the mechanical properties of the material at the macro-level (Saliu et al., 2021). Hence, in this research, we evaluated the degradation of the spunbond and meltblown polypropylene layers by FTIR analysis and the results were reported in Fig. 5. The degradation can be confirmed from the FTIR results of both spunbond and meltblown nonwoven fabrics before and after weathering. Fig. 5 a) indicates the normal polypropylene curve obtained from the non-weathered sample. The peaks obtained from the analysis showed the standard peaks that represent the polypropylene fiber. CH stretch vibrations at 2950, 2918, and 2836/cm, CH₂ deformation, and Symmetric CH₃ formation were denoted at 1458, and 1378/cm wavelength respectively. The isotactic bands at 1170, 976, and 844/cm represent the polypropylene fiber (Akarsu et al., 2021; Rathinamoorothy and Raja Balasaraswathi, 2022). In the case of degraded spunbond (Fig. 5 b) and meltblown (Fig. 5 c), several variations were reported due to the effect of degradation.

For instance, changes in the region 1700–1750/cm were very prominent in the degraded samples, for both spunbond and meltblown structures (region 3 in Fig. 5). A reduction in the peak density and broadening of the peak at 3400/cm also represents the formation of carboxylic groups in the weathered samples (region 1). Saliu et al. reported that the changes in this region are the representatives of multiple carboxyl groups and carboxylic acids that are formed during the degradation of nonwovens due to the radical oxidation process. This was confirmed when similar results were noticed from the FTIR analysis of polypropylene masks that end up in the environment (Saliu et al., 2021). Other researchers also reported that the changes in the polypropylene structure at 1750–1700/cm (carbonyl peak, region 3) and 3300–3500/cm (the hydrogen-bonded hydroxyl group of alcohol) are evidence of photodegradation (region 1) (Uheida et al., 2021). The sunlight exposed the nonwoven fabrics to UV radiation and hence it broke the C–C and C–H bonds in the polypropylene structure and developed alkoxy radicals and peroxy radicals. These radicals along with carbonyl groups led to chain scission in the structure. This was confirmed by the hydrophilic nature of the weathered mask compared to the control samples (Wang et al., 2021). The weathered samples also showed a reduction in peaks in the wave number of 2800 and 3000/cm (region 2) and at 1450 and 1350/cm (region 4). These reductions correspond to the C–H stretches, and C–H bends respectively (Jung et al., 2018; Zvekic et al., 2022). A higher alteration in the chemical structure of the meltblown fabric (Fig. 5 c) in the mentioned 1600–1700, 3400–3600, and 800–1100/cm regions indicate severe damage to meltblown layers than in the spunbond samples (region 5). These findings were in line with the findings of researchers (Wang et al., 2021), who mentioned the higher damage of meltblown fabric after UV exposure.

These degradation effects ultimately affect the mechanical strength of the fibers and fabric structures as shown in Fig. 4. Hence, the weathered masks were able to release a relatively higher amount of microfibers compared to the control sample. These findings were supported by the findings of Barish et al. (Barish, 1989). They reported the degradation of polypropylene fibers to sunlight exposure. Exposure of polypropylene fiber in the sunlight creates deep surface cracks in the fibers against the axis of the fiber. The surface cracks in the fiber increase the surface area and develop separation between the core and surface layer of the fiber. This greatly affects the integrity of the fibers and breaks them into parts. This was expected due to the brittle nature of the surface layer of polypropylene fiber. The degradation was also evident by the individual tensile fracture of the core and sheath part of the fiber. The study proposed a shrinkage mechanism in the polypropylene fiber that causes differentiation shrinkage in the core and sheath fiber. Hence the surface was more exposed to air and degrades higher, and this creates an enormous amount of stress in the core and aids in fiber breakage (Barish, 1989; Wang et al., 2021). A similar degradation of polypropylene film into fine particles with a 30-day weathering process was also reported in the literature (Gogotov and Barazov, 2012). While analyzing different mask layers after the different duration of the UV

![Fig. 4. Microscopic view of Meltblown (A & B) and Spunbond (C & D) samples before (A & C) and after (B & D) weathering.](image-url)
irradiation process, studies mentioned that the load-bearing capacity of the weathered mask decreased in line with the increase in UV light exposure hours. Hence the study reported a strength loss after weathering process (Wang et al., 2021).

3.2. Effect of dry and wet states exposure

In this analysis, the rubbing and soaking process was performed to mimic the exposure of the mask in the environment while it is improperly disposed. The rubbing process mainly used here represents the mechanical forces applied to the fabric during the collision with rock and sand caused by wind, waves, and tides. The mechanical actions are imparted on the mask during several transportation processes namely weathering process, surface runoff by air and water in the land and river beds, bottom currents upon the seafloor, waves-rocks interaction, and also during the movements through pipes and drains (Duan et al., 2021; Kane et al., 2020; Morgana et al., 2021). Microfiber release from the non-woven fabrics varied when they are exposed to different conditions like dry and wet states. Fig. 6 illustrates the quantity of microfiber released from the non-woven fabrics under different conditions. The microfiber release from the fabric was significantly ($p < 0.05$) higher in the case of dry state than in the wet states (Rubbing and Soaking). It is in line with the previous study (Rathinamoorthy and Raja Balasaraswathi, 2022) where the microfiber release from the tri-layer surgical masks was analyzed. In the dry state, the fuzz formation ability of fabrics was higher which initiates the fiber release and so the release is noted higher than in the wet state (Wan et al., 2014; Zambrano et al., 2019). Similarly, in the wet stage, a higher microfiber release was noted with the wet rubbing experiment over the soaking in water. The significantly higher microfiber release ($p < 0.05$) in the wet rubbing process was mainly related to the mechanical rubbing process introduced at this condition over-soaking. A similar trend was noted in the case of all the samples analyzed. Hence, it is evident that irrespective of the fabric characteristics, the external experimental conditions have a higher impact.

3.3. Influence of internal parameters on microfiber release

Apart from the external environment, the intrinsic characteristics of the non-woven fabrics were noted to have a significant impact on the microfiber release. The most commonly seen variations in the non-woven fabrics which are used in the single-use disposable masks are the variations in the manufacturing method (spunbond and meltblown) and fabric weight (grams/sq.m). Hence, the effects of those parameters on microfiber release are analyzed in this study.

3.3.1. Effect of fabric manufacturing method

The microfiber release of spunbond and meltblown fabrics is compared in Fig. 7. The microfiber release of meltblown fabrics was significantly higher than the spunbond fabrics in dry state conditions. In wet states, the case is the opposite where the spunbond fabrics shed higher fibers than the meltblown fabrics. However, the difference is not significant ($p > 0.05$) in any case. The difference between the spunbond and meltblown nonwoven fabric at constant GSM is mainly related to their structural difference. From Table 3, it can be evident that for a given GSM, the meltblown fabric possessed a comparatively lower bursting strength (4.6, 4.8 kg/sq.cm) than the corresponding spunbond fabric (5.4, 5.7 kg/sq.cm). This might be attributed to the method of bonding difference. In the spunbond fabric, all the fibers in the structures are firmly bonded together at several points (Fig. 4, c), whereas in the meltblown fabric, they were fused together at the fiber level. The structure of the meltblown fabric formed not only through the fiber fusing but also formed with branching, and interlacement of fibers (Lee and Wadsworth, 1990). So, the structure is expected to have lower strength than the spunbond fabric. Moreover, the higher bursting strength of spunbond fabrics also reveals that the structure is more compact and entangled, as a result, a better load sharing by the individual filaments before the structural breakdown can be noticed (Das and Raghav, 2010). Similarly, the structural effect was also evident from the variation in abrasion resistance. For the same GSM, the spunbond structure showed higher abrasion resistance by withstanding 601 cycles.
whereas the meltblown fabrics were torn after two cycles. In addition to this, for the similar thickness of fabric, meltblown fabrics have a greater number of fibers than the spunbond fabrics because of the lower diameter of fibers used in meltblown fabrics. Hence, due to the poor mechanical properties and higher number of fibers in the unit area of meltblown fabrics, a higher release behaviour was noted in meltblown fabrics than the spunbond fabric at all the stages.

3.3.2. Effect of fabric weight (GSM)

The increase in fabric weight per unit area of the fabric increases the microfiber release per unit area of the fabric in case of both meltblown and spunbond fabrics in all experimental conditions. Fig. 8 shows the relationship between microfiber release from spunbond and meltblown fabrics with GSM. In the case of spunbond fabrics, the direct influence of fabric GSM on microfiber release has been visualized with a strong positive correlation ($R = 0.86$ for rubbing in a dry state; $0.77$ for rubbing in a wet state; $0.88$ for soaking in water). This can be attributed to the nature of fibers and their distribution in the fabric structure. The GSM of the fabric is effectively dependent on the fabric thickness, the number of fibers distributed in the unit area and the denier of filaments used. In that aspect, these factors were analyzed and correlated with microfiber shedding. The diameter of fibers in all the samples was analyzed and no significant difference ($p > 0.05$) has been noted between the samples. Also, the negligible effect of filament diameter on GSM has been confirmed by the poor correlation ($R = -0.13$) between filament diameter and GSM (Table 4). Similarly, the thickness of the fabrics was correlated with GSM, which yielded a strong positive correlation ($R = 0.95$) which denotes that the increase in thickness increases the GSM.

A previous study, which analyzed the microfiber release of polyester knitted fabrics reported that the increase in thickness can increase the microfiber release of the fabrics (Raja Balasaraswathi and Rathinamoorthy, 2021). From this study, it was evident that the increased thickness increases microfiber shedding also in the case of non-woven fabrics. Lastly, the fiber distribution was analyzed and correlated with GSM and microfiber shedding. The distribution of fibers in the unit area has been visualized by analyzing the threshold images as shown in Fig. 9, which showed the fraction of the area occupied by fibers in the unit area. Results clearly showed that GSM is increased with the increment in the fibers distributed in the unit area. The correlation analysis of fabric GSM and the percentage of area occupied by the fibers in the unit area showed that they have a strong positive correlation ($R = 0.97$). Thus, the greater number of fibers in the unit area of the fabrics leads to increased microfiber release per unit area of the fabric while increasing the GSM. In the case of meltblown fabrics also, a similar trend was reported. An increment in the fabric GSM increases the microfiber release ($p < 0.05$) compared to the similar (GSM) spunbond nonwoven. The higher microfiber release in the higher GSM fabric can be similar to the spunbond fabrics, where a higher thickness and higher number of fibers per square unit are the main reasons. It was evident from the analysis of thickness and percentage of area occupied by the fibers in the unit area (Table 5). The fabric with higher GSM (30 GSM) comparatively had a higher thickness and higher number of fibers in the unit area than that of 25 GSM fabric. This is attributed to the higher microfiber release with higher GSM in the case of meltblown fabrics.
3.3.3. Effect of physical properties

Physical properties of non-woven fabrics including abrasion resistance and bursting strength were analyzed. Though these properties were mentioned to have a better role in the difference in the microfiber release of spunbond and meltblown fabrics (as discussed earlier), their effect among the same structure was noted as different. While comparing spunbond fabrics with different abrasion resistance levels, fabrics which are having better abrasion properties are found to release more fibers. From Table 4, the correlation analysis of abrasion resistance and microfiber release showed a higher correlation ($R = 0.92$) for dry rubbing and a medium correlation for both wet rubbing and soaking (respectively $R$ values of 0.71 and 0.74). This can again be related to the GSM of the fabrics. The higher abrasion resistance of the samples was due to the higher GSM and higher % of fibers per unit area (strong

Fig. 7. Effect of Fabric production method on microfiber release from spun bond and meltblown fabric at a) dry rubbing, b) wet rubbing and c) wet soaking.
positive correlation). This in turn increases the microfiber release per unit area of fabric. Thus, increased abrasion resistance results in increased microfiber release. Similarly, when the bursting strength of the fabrics was considered, microfiber release was noted to increase with an increase in bursting strength. Again, this can be related to the increase in GSM, thickness, and % of the area occupied by fibers with increased bursting strength. Similar results were noted in the study by Das and Raghav, who reported an increase in bursting strength of spunbond fabrics with increased GSM because of the presence of a greater number of fibers in the unit area (Das and Raghav, 2010). Since the increased GSM, thickness, and the number of fibers per unit area increases microfiber release, fabrics with higher bursting strength are noted to release higher fibers. However, it is important to understand, that better physical strength is essential for reducing microfiber release from the fabrics. However, their effect becomes diminished when the structural parameters like GSM, thickness, and number of fibers per unit area come into play. This was evident from this study when the meltblown and spunbond fabrics with similar structural parameters showed a difference in the microfiber release because of the poor mechanical properties of meltblown fabrics. However, the effect of mechanical properties (bursting strength and abrasion resistance) was superseded by the structural parameters like different GSM, thickness, and the

Fig. 8. Effect of fabric GSM on microfiber release behaviour of spunbond and meltblown non-woven fabrics at a) dry rubbing, b) wet rubbing and c) wet soaking.
number of fibers per unit area. The results of various research works performed on the disposable tri-layer mask and the results of the current study are compared in Table 6.

This analysis of microfiber release from the non-woven fabric structures revealed that it can make a greater contribution to the microfiber pollution in the environment. At the beginning of the COVID-19 pandemic, WHO estimated 89 million face masks per month globally to handle the spread of the COVID virus (WHO, 2020a). Up to March 2022, WHO alone has shipped 12.4 million medical gowns and 0.22 billion masks to various countries to handle the COVID crisis (WHO, 2022). Other researchers estimated that in India alone, approximately a maximum of 4640 million masks are being discarded per week and

| Fabric GSM | Filament (mm) | Thickness (mm) | % of area occupied by fibers | Bursting Strength | Abrasion Resistance | Dry Rubbing | Wet Rubbing | Wet Soaking |
|------------|---------------|----------------|----------------------------|------------------|---------------------|-------------|-------------|-------------|
|            | 1             | 0.1293         | 0.9500                     | 0.9654           | 0.9393              | 0.5799      | 0.7106      | 0.8771      |
| Thickness (mm) | 0.2299       | 0.8161         | 0.1177                     | 0.8401           | 0.9471              | 0.9567      | 0.9278      | 0.4149      |
| % of area occupied by fibers | 0.8401         | 0.9471         | 1                          | 1                | 1                   | 1           | 1           | 1           |
| Bursting Strength | 0.9393         | 0.1862         | 0.8161                     | 0.9471           | 1                   | 1           | 1           | 1           |
| Abrasion Resistance | 0.9621         | 0.08062        | 0.8305                     | 0.9992           | 0.9567              | 1           | 1           | 1           |
| Dry Rubbing | 0.8803         | 0.4285         | 0.7674                     | 0.9395           | 0.7799              | 0.9278      | 1           | 1           |
| Wet Rubbing | 0.7746         | 0.4856         | 0.7382                     | 0.6932           | 0.8780              | 0.7106      | 0.4149      | 1           |
| Wet Soaking | 0.8771         | 0.1547         | 0.9203                     | 0.7453           | 0.8499              | 0.7490      | 0.5464      | 0.9287      |

Fig. 9. Microscopic Images (a) 8-bit images (b) threshold images of Spunbond fabrics (c) 8-bit images (d) threshold images of Meltblown fabrics.
estimated that it leads to the generation of 12,255 tons of polypropylene waste per week. The study also estimated the waste generated from the UK, US, Australia, India, Srilanka, and Singapore and reported a cumulative figure of 6090 million masks/week as 16,081 tons of polypropylene waste is generated per week (Selvaranjan et al., 2021). Based on this data, we estimated the actual consumption of spunbond and meltblown fabric in the mask. In the tri-layer mask, the middle layer (filtration layer) is made of meltblown polypropylene fabric, and the other two layers (outermost layer and skin contact layer) are made of spunbond polypropylene fabric. By cutting open a mask, we calculated the size of all the layers (15 cm × 16 cm) and estimated the approximate microfiber emission in India alone based on the consumption rate (4.64 × 10⁹ masks/week) as provided by literature (Selvaranjan et al., 2021). The results are provided in Table 7, which shows the consolidated release of microfiber at dry and wet state exposure.

Based on this information, a single mask can emit 149.69 ± 42.49 mg of microfibers at dry state abrasion and 34.53 ± 14.37 mg at the wet stage. By considering the Indian population (1.38 billion as of 2020 estimation), it can be estimated that 427.39 ± 104.07 tons of polypropylene microfibers waste are emitted into the environment (average of dry and wet emission) from the disposed masks. This can be increased by 2.9 and 4.9 times if we consider the effect of natural weathering for dry and wet states respectively. Other than the environmental impact of improper mask disposal, a study estimated the impact of usage and production by relating carbon footprints. The study estimated that the use of surgical masks can emit 240 kilotons of carbon dioxide in Italy alone from March 2020 to December 2021. However, the study reported 35 times less pollution (7 kilotons) with reusable woven/knitted fabric masks. Similarly, the transportation of masks and production of the masks also showed a significant impact on carbon dioxide emissions. After including this data, in the estimated period, in Italy alone, approximately 350 kilotons of carbon dioxide were emitted (Cornelio et al., 2022).

This estimation evidences the seriousness of the improper disposal of masks. Based on these results, we can understand that such an amount of plastic pollution in the land and aquatic sources will become a challenging consequence in achieving the Sustainable Development Goals (SDG) of the 2030 agenda. The SDG 14 of the UN mainly focuses on attaining clean and healthy oceans. Various initiatives were made by the UN to reach the goals along with some partnering programs. Since the agenda of 2030 is made before the pandemic, the challenges in achieving them had increased due to the consequences of the COVID-19 pandemic. Though the pandemic had impacted ocean health positively with a reduction in coastal tourism, international shipping, and overfishing (due to decrement in consumption of seafood in restaurants), the negative impact increased with the Personal Protective Equipment (PPE) wastes (Thompson, 2021). It has been reported that as of August 2021, 8.4 ± 1.4 million tons of pandemic-related plastic wastes were generated from 193 countries across the world where around 25.9 ± 3.8 thousand tons of waste ended up in oceans (Peng et al., 2021). Hence, it is very crucial to stretch the efforts of initiatives in data collection about the impact and to trace the progress. Though the data related to the PPE consumption and disposal is found to be made significantly, their consecutive effect like microfiber release potential is less known.

From the microfiber release potential of different materials that are being used in the PPE items like 100% PP spunbond and meltblown fabrics, a higher environmental impact is evident. A higher impact of meltblown layers alarms the requirement of an alternative filtration layer in the middle layer of the mask. As the manufacturing method was noted as the main reason for the higher shedding of fibers, researchers and industries can think of other structures for the filtration application. Additionally, the nonwoven with higher thickness and GSM can release more fibers into the environment. Based on these factors industries may consider either selecting different manufacturing technology over nonwoven or modifying the fabric parameters. Though the application of disposable PPEs is unavoidable, policymakers and governments of the countries must have to plan proper waste management strategies to handle such disposable PPEs. In such applications, the manufacturer can also provide safe disposal instructions on their product to educate the consumers. Last but not least, is the knowledge of the general public. Efforts must be made to educate the general public (either by local government or globally) through media to understand the impact. Such sustainable practices from academic researchers, manufacturers (production phase), governments, policymakers (disposal phase), and the general public (use and disposal phase) will help us to mitigate microfiber pollution and effectively attain SDG 14.

### 4. Conclusions and future directions

This study analyzed the microfiber release behaviour of different non-woven structures that are being used in these disposable masks from the perspective of textile parameters and properties. The important findings of the study are summarized as:

- Natural weathering has a greater impact on melt-blown fabrics than spun-bond fabrics which can be related to the finer fibers and more number of fibers used per unit area in the melt-blown fabrics.
- While considering external factors, microfiber release is higher in the case of dry state experiments than in the wet state because of the higher fuzz formation in the dry state. While comparing wet state rubbing and soaking, wet state rubbing released more microfibers than soaking which is due to the mechanical actions during the rubbing process.
- While considering the fabric production method (Spunbond and Meltblown), a higher release has been noted with meltblown structures. The difference in the fusing method, poor mechanical properties (bursting strength and abrasion resistance), finer fibers, and more number of fibers per unit area are noted to increase the microfiber release from meltblown fabrics than that of spunbond structure.
- When the effect of fabric GSM is analyzed, the microfiber release increased with increasing GSM, which is due to the increased thickness and number of fibers per unit area of the fabric.
- When the physical properties such as abrasion resistance and bursting strengths are analyzed, their impact were prominent when other structural parameters like thickness, GSM, and the number of fibers per unit area are similar. However, when the structural parameters are varied, then their influence overtook the influence of physical properties.

### Table 5

| Sample | GSM | Thickness (mm) | Filament Diameter (mm) | Abrasion Resistance (End Cycles) | Bursting Strength (kg/cm²) | % of the area occupied by fibers in unit area |
|--------|-----|----------------|------------------------|---------------------------------|----------------------------|---------------------------------------------|
| S15    | 15  | 0.15           | 0.0277                 | 60                             | 5.2                        | 65.14                                       |
| S20    | 20  | 0.152          | 0.0275                 | 530                            | 5.4                        | 78.08                                       |
| S25    | 25  | 0.182          | 0.0267                 | 601                            | 5.4                        | 80.75                                       |
| S30    | 30  | 0.192          | 0.0278                 | 900                            | 5.7                        | 88.21                                       |
| M25    | 25  | 0.175          | 0.0064                 | 2                               | 4.6                        | 81.67                                       |
| M30    | 30  | 0.198          | 0.0081                 | 10                             | 4.8                        | 85.63                                       |
### Table 6
Results of the current study compared with the findings of the existing literature.

| S. No. | Reference | Materials evaluated | Average Length of microfiber noted | Average quantity of microfiber release | Key findings |
|--------|-----------|---------------------|------------------------------------|----------------------------------------|--------------|
| 1      | Sullivan et al. (2021) | Disposable plastic face mask | 25 μm - 25 mm | - | - |
| 2      | Wang et al. (2021) | Disposable tri-layer mask | 10-250 μm | - | - |
| 3      | Shen et al. (2021) | Disposable surgical mask | 0.5-3.8 mm | - | - |
| 4      | Salihu et al. (2021) | Surgical mask | 25 μm - 5 mm | - | - |
| 5      | Morgana et al. (2021) | Tri-layer surgical face mask | Size classes 0.1-0.5 μm and <0.1 μm | 2.1 ± 1.4 × 10¹⁰ items/mask | - |
| 6      | Ma et al. (2021) | Face masks | Middle Layer - 57.2 ± 18.48 mm, Outer Layer - 75.8 ± 19.68 nm, Inner Layer - 88.4 ± 17.69 mm | 1.3 ± 4.4 × 10⁷ Microparticles/mask, SEM - 1.6-3.8 × 10⁷ Nanoparticles/mask, AFM - 2.8-6.0 × 10⁷ Nanoparticles/mask | - |
| 7      | Chen et al. (2021) | Surgical Disposable face mask | 100-500 μm | - | - |
| 8      | Rathinamoorthy and S. Raja Balasaraswathi (2022) | Reusable and re-washable face masks (Polypropylene – Spunbond fabrics) | New masks - 0.119-2.042 mm, Weathered masks - 0.091-2.621 mm | - | - |
| 9      | De Felice et al. (2022) | Reusable and re-washable face masks | Polyurethane - 1.33 ± 0.05 mm, Polyamide - 0.72 ± 0.25 mm, Polyester - 0.51 ± 0.03 mm, Polypropylene - 0.93 ± 0.28 mm, Cotton - 0.83 ± 0.08 mm | Polyurethane - 541.33 ± 51.84 microfibers/mask/wash, Polyamide - 28.33 ± 9.83 microfibers/mask/wash, Polyester - 133.66 ± 41.77 microfibers/mask/wash, Polypropylene - 98 ± 11.93 microfibers/mask/wash, Cotton - 823.00 ± 112.53 microfibers/mask/wash, Disposable PP mask - 85.33 ± 6.93 microfibers/mask/wash | - |
| 10     | Wu et al. (2022) | Common mask, Surgical mask, Face filtering piece mask | 47.78 μm - 3.93 mm | 272 ± 12.49 items/sq.cm of mask | - |
| 11     | Liang et al. (2022) | Disposable face masks | Size range – 100 to 500 μm; less than 100 μm | N-95 masks – 80.1 ± 71 to 2667 ± 97 microparticles/mask, Medical surgical masks – 1136 ± 87 to 2343 ± 168 microparticles/mask | - |

- Face masks are prone to release organic and inorganic leachates including lead, silicon-containing fragments, cadmium, antimony, copper, polyamide monomers, oligomers, dye molecules and polyethylene glycol.
- Physio-chemical changes during weathering increase the microfiber release from masks.
- The middle layer of the mask is more sensitive to UV irradiation and releases more microfibers.
- Physical abrasion by sand in the environment can enhance the microfiber release.
- The microfiber release from the masks increases with the increase in the number of washes.
- Weathering can cause the masks to become more fragile which led to increased microfiber release.
- The use of detergents or alcohol increased the potential of the microfiber release of masks.
- Photo-oxidative degradation of polypropylene leads to the breakage of material and release of microfibers.
- The microfiber release has no linear correlation with weight loss and deterioration of fabrics.
- Microfiber release followed a lognormal curve at increasing shear stress.
- The middle layer of the mask released more fibers than the inner and outer layers.
- The nasal mucus of the people wearing masks is different for different mask types.
- No significant difference was noted between the washes.
- Abrasion and ageing of masks during usage increases the microfiber release of used masks.
- Both fibers and fragments were released from the masks with fibers as dominant (70%).
- The microfibers released from the masks possess the risk of inhalation.
- Abrasion and ageing of masks during usage increases the microfiber release of used masks.
- Both fibers and fragments were released from the masks with fibers as dominant (70%).
- The microfibers released from the masks possess the risk of inhalation.
- Exposure to sea water can increase microfiber release up to 97.98%.
- Cotton masks release higher microfibers than synthetic ones.
- Cotton release higher fibers due to lower tenacity, higher hydrophilicity, and higher wet abrasion.
- Reusable and disposable PP masks showed a similar level of microfiber release.

(continued on next page)
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There are two layers of spunbond fabric in a single mask and hence the area is calculated as 480 sq. cm (2

Estimation of microfiber emission from disposable masks in India.

Table 7

| S. No | Reference | Materials evaluated | Average Length of microfiber noted | Average quantity of microfiber release | Key findings |
|-------|-----------|---------------------|-----------------------------------|--------------------------------------|-------------|
| 12    | This study| Polypropylene Non-woven, Spunbond, Meltblown | 0.26 to 0.78 mm | Normal medical masks – 1034 ± 119 to 2547 ± 185 microparticles/mask. Dry state: Spunbond fabrics – 296.82 ± 40.25 to 773.21 ± 137.95 fibers/sq.cm, Meltblown fabrics – 898.17 ± 14.43 to 1347.16 ± 113.55 fibers/sq.cm. Wet state: Spunbond fabrics – 37.36 ± 0.76 to 333.19 ± 9.26 fibers/sq.cm, Meltblown fabrics – 32.03 ± 4.96 to 175.27 ± 2.67 fibers/sq.cm. | Microfiber release kinetics showed that on first day the release increased rapidly, afterwards, the release rate started decreasing. Meltblown fabrics showed higher microfiber release than spunbond fabrics. Weathering affects meltonblown fabrics more than the spunbond fabrics. GSM, abrasion resistance, bursting strength, and fabric thickness have a positive correlation with the microfiber release. |

Table 6 (continued)

| Average Microfiber Release for different GSM | Size of Individual Layer used in the Mask (sq. cm) | Microfiber release (mg) from the layer in a single mask (dry state) | Microfiber release (mg) from the layer in a single mask (wet state) | Estimated microfiber release in India per week at dry state (in Tons) | Estimated microfiber release in India per week at wet state (in Tons) |
|--------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Unweathered Masks                          | Spun Bond: 480 ± 14.43                        | 18.41 ± 7.33                                               | 328.60 ± 66.96                                                  | 85.42 ± 34.01                                                | 195.58 ± 57.16                                  |
|                                            | Meltblown: 240 ± 28.06                        | 16.12 ± 7.04                                               | 365.96 ± 130.20                                                 | 74.80 ± 32.67                                                | 156.22 ± 66.68                                  |
|                                            | Total: 720 ± 42.49                            | 34.53 ± 14.37                                              | 694.56 ± 197.16                                                 | 160.22 ± 66.68                                                | 302.80 ± 77.16                                  |
| Weathered Masks                           | Spun Bond: 197.17 ± 28.74                     | 42.15 ± 12.32                                              | 914.87 ± 133.35                                                 | 195.58 ± 57.16                                                | 391.16 ± 113.35                                 |
|                                            | Meltblown: 236.73 ± 56.14                     | 127.08 ± 22.11                                             | 1098.43 ± 260.49                                                | 589.65 ± 102.59                                               | 1196.03 ± 215.21                               |
|                                            | Total: 433.9 ± 84.88                          | 169.23 ± 34.43                                             | 2013.3 ± 593.84                                                 | 785.23 ± 159.75                                               | 2492.19 ± 321.75                               |

*a There are two layers of spunbond fabric in a single mask and hence the area is calculated as 480 sq. cm (2 × 240 sq. cm).

As far as the current study is concerned, the following limitations are noted:

- The simulation steps used in the estimation of microfiber release in the aquatic environment can be improved based on different natural conditions with the development of standards.
- The weathering process can be extended for a longer duration like 6–12 months to obtain more reliable data and also methods can be developed to measure the microfiber release into the terrestrial environment during the weathering process.
- Though the effects of GSM and fabric structure were examined, the impact of polymer types used and manufacturing process parameters on the microfiber release characteristics are not evaluated. Such evaluations can fine-tune the production process so that the mask can release comparatively lesser fibers.

In the post-COVID situation, the use of masks is unavoidable, and it is very difficult to completely educate the world population regarding the environmental impact associated with it. Hence, future studies should be focused on two major aspects namely, i) in the textile viewpoint, a modified fiber/fabric production process that reduces the microfiber release or special treatment to control such release of microfibers in the user phase. ii) suitable waste handling methods for disposed-of masks and other synthetic textiles must be devised globally to control such improper disposal. Though some of the circular fashion concepts prevailing in the fashion industry help in solving these issues partially, disposable (one-time use) products like a mask can not be replaced completely with such ideology. It is important to devise such products/processes at the global level to address this issue effectively.

Credit author statement

R. Rathinamoorthy: Conceptualization, Methodology, Formal analysis, Writing – review & editing. S. Raja Balasaraswathi: Conceptualization, Investigation, Resources, Data curation, Writing – original draft

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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