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## Semi-transparent and eco-friendly face masks for PM<sub>0.3</sub> filtration via biomimetic-fractal nanofibers

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**Abstract**

To address the need for sustainable high-performance face masks, we demonstrate a strategy that utilizes zein for efficient nanofabrication. An electrospinning process controllably splits the fluid jet, allowing for the creation of face masks composed of fine, fractal-like nanofibers without the need for impurity excipients. This process, enabled by an dipole-force-induced interfacial fluctuation mechanism that we identified, results in face masks that achieve exceptional air filtration performance, surpassing that of commercial N95 masks, while reducing both weight and thickness by half. The significant reduction in material use grants the face masks high optical transparency, facilitating unobstructed facial recognition. Crucially, the pure zein composition allows for the reprocessing of the face masks, contributing to further resource conservation. This work provides a simple, eco-friendly solution for advanced personal protection and points the way toward sustainable wearable devices.

## Introduction

Face masks have been an indispensable personal protection equipment to filter out airborne particulate matters (PM) including viruses during the COVID-19 pandemic<sup>[1-3]</sup>. These masks typically use membranes constructed by melt-blown polymer fibers such as polypropylene (PP) for high air filtration performances<sup>[4, 5]</sup>. A large amount of static charges can be applied on these fibers to enhance the air filtration effectiveness by the electrostatic adsorption effect<sup>[6-8]</sup>. Unfortunately, these face masks may fail due to charge dissipation in humid conditions, and they are difficult to degrade after use, which could lead to significant white pollution. Face masks based on electrospinning processes have small-size fibers with large surface-area-to-volume ratio for better filtration efficiencies<sup>[9-11]</sup>. Since a wide range of biodegradable and bio-based substances such as proteins and celluloses can be processed by means of electrospinning<sup>[12-14]</sup>, eco-friendly face masks could be constructed. It is worth mentioning that due to the renewability and biodegradability of raw materials, bio-based materials are being sought as alternatives to petroleum-based materials and are being applied in a wide range of fields, with air filtration being a notable example<sup>[15-17]</sup>. Furthermore, bead-like, curled, porous, and bimodal structures have been constructed by adjusting electrospinning parameters and solution properties<sup>[18-21]</sup>. Among these configurations, bimodal structures have both coarse fibers to maintain the structural stiffness with fewer fibers for reduced air resistance and fine fibers to maintain effective filtrations<sup>[22-24]</sup>. As an evolutionary form of bimodal structure, biomimetic-fractal construction (e.g., branch and leaf vein) enables reduced but strong skeleton structures with ultrafine nanofibers. It reduced overall weight

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for the semi-transparent property without reducing the filtration effectiveness to enable applications such as face recognition even wearing these face masks. Previously, the biomimetic-fractal features have achieved high air filtration performance under a mass per area of  $0.5 \text{ g/m}^2$ , which is only 3% of the commercial N95 mask<sup>[25]</sup>. It results in greater convenience in daily life, social events, and human-machine interaction applications. This work focuses on these eco-friendly biodegradable face masks via biomimetic-fractal nanofibers for improved environmental friendliness, filtration performance, and comfort.

The splitting behavior of the electrospinning jet is the key in inducing the formation of biomimetic-fractal nanofibers<sup>[26-28]</sup>. Previously, the jet splitting behavior is linked to the Coulomb explosion, characterized by an instantaneous release of high-density charges without clear directionality<sup>[29-31]</sup>. As such, a high conductivity is the key for jet splitting and ionic materials are generally utilized for this purpose<sup>[32-34]</sup>. However, in our previous work, it is observed that high conductivity may not be the main reason for jet splitting<sup>[35,36]</sup> and this issue is further investigated in this work as the first task. The second task is to use bio-based materials for eco-friendly face masks. These materials generally possess abundant functional groups and complex molecular conformations, requiring precise control over processing parameters<sup>[37-39]</sup>. The third task is the model of electric charges in the hydrodynamic mechanisms for jet splitting. A dipole-oriented electrospinning model is proposed, including jet inability, ribbon-like stretching, and jet splitting with experimental test and numerical simulations. Overall, these studies result in the efficient manufacturing of zein nanofibers with biomimetic fractal structures by regulating solvent

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compositions for the production of face masks with high air filtration efficiency, semi-transparent, and lightweight properties. Furthermore, these zein membranes can be reprocessed to meet resource recycling and sustainable development requirements.

## Results

### Analysis and Application of the Jet Splitting Mechanism

Biodegradable zein has been chosen in this study in various solutions with jet splitting or stretching behaviors as shown in Fig. 1a. It is the principal protein of corn and soluble in various solvents such as acetic acid (HAC), formic acid (FA), ethanol (ETOH), dimethyl sulfoxide (DMSO), and water. Solutions based on HAC or ETOH are more prone to jet splitting for the formation of biomimetic-fractal nanofibrous membranes in our study, with a conductivity of only 66  $\mu\text{S}/\text{cm}$  and viscosity of 847  $\text{mPa}\cdot\text{s}$ . Solutions based on water or DMSO have conductivity in the range of 1757  $\mu\text{S}/\text{cm}$  and viscosity of 543  $\text{mPa}\cdot\text{s}$ , with uniform fiber sizes and without jet splitting. These results contrast with the jet splitting conditions based on the Coulomb explosion mechanism (Supplementary Fig. 1), which states that high conductivity and low viscosity are favorable for jet splitting. As such, solution properties, jet behavior, and fiber morphology are further investigated to characterize the jet splitting mechanism (comparative experimental results conducted under identical conditions are presented in the section on dipole-oriented electrospinning model). Fig. 1b illustrates the fractal geometry in nature and biomimetic-fractal fibers fabricated by the electrospinning process at the left; the dipole-oriented jet splitting

mechanism with fluctuation and anisotropic stretch-tear induced by the dipole force at the right. Electrohydrodynamic simulation results (comparative simulations conducted under identical conditions are presented in the section on analysis of jet splitting based on simulation) show that the formation of multiple fluctuation points at the jet interface and the anisotropic stretching-tearing are main factors to induce jet splitting. Furthermore, the strong directional effect of the dipole force and low surface tension can be utilized to control jet splitting to produce biomimetic-fractal nanofibers. Specifically, the directional effect of the dipole force of charged fluids has been identified as a vital parameter for jet jetting, cylindrical stretching, and ribbon-like stretching, which has not been previously reported.

With sufficient mixtures of ultrafine fibers at a mass per area of  $0.45 \text{ g/m}^2$ , a zein biomimetic-fractal membrane exhibits  $2\times$  better air filtration efficiency as compared with those of the commercial N95 mask (details in section of air filtration test). The proposed fractal structure improves filtration performance by about 62% and optical transparency by nearly 60% compared to existing bimodal structures, which reflects the advantages of the existing design (Supplementary Note 1 and Supplementary Fig. 2). The zein membrane is deposited on polylactic acid (PLA) non-woven fabric and subsequently assembled into a face mask (Supplementary Fig. 3a), with a weight of 0.0524 g ( $4 \text{ cm} \times 4 \text{ cm}$ ) and a thickness of 0.139 mm (Supplementary Fig. 3b), while the commercial N95 mask has a weight of 0.1673 g ( $4 \text{ cm} \times 4 \text{ cm}$ ) and a thickness of 0.375 mm (Supplementary Fig. 3c). Fig. 1c shows the transmittance measurement characterizations. As expected, membranes with low basis weight result in high transmittance up to 83% ( $0.45 \text{ g/m}^2$

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zein), which is about 4 times higher than that of the commercial N95 mask core layer (23%), as shown in Supplementary Fig. 4a. Our mask is made by laminating the zein membrane with PLA non-woven fabric, with the latter slightly reducing the transmittance to 70%, which facial features can also be used to facilitate social interactions, thus enabling facial recognition through access control systems (Fig. 1d). Conversely, wearing the N95 mask cannot be recognized through facial recognition (Supplementary Fig. 4b). Furthermore, the lightweight ( $\leq 2 \text{ g/m}^2$ ) and porous characteristics enable zein membranes to maintain good 2-16  $\mu\text{m}$  infrared transmittance at 81.3%, which is 2.13 times higher than that of a commercial N95 mask core layer (38.2%), as shown in Supplementary Fig. 5a. A prototype mask has a measured temperature close to the body temperature (Supplementary Fig. 5b) with good moisture permeability at  $7.88 \text{ kg/m}^2/\text{day}$ , which is 1.45 times higher than that of a commercial N95 mask (Fig. 1e). Supplementary Fig. 5c shows that when covering the bottle mouth filled with  $60 \text{ }^\circ\text{C}$  water, our mask can penetrate more water vapor compared to the commercial N95 mask. The heat dissipation enhancements due to the synergistic effects of better heat radiation and moisture evaporation result in an exhaled temperature of  $33.2 \text{ }^\circ\text{C}$ , which is significantly higher than those by wearing commercial N95 mask at  $29.1 \text{ }^\circ\text{C}$ , as shown in Fig. 1f. Microscopic chemical structure analysis further demonstrates that the good heat radiation is due to the lightweight matrix structure of the zein membrane, which reduces the obstruction to infrared. Similarly, this is also an important reason for the improvement of transparency. On the other hand, the enhanced moisture permeability is closely related to the low hydrophobicity of the zein membrane, thereby promoting the adsorption-desorption process of water vapor

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(Supplementary Note 2). Furthermore, the zein is rich in polar functional groups such as amino, carboxyl, and hydroxyl groups (Supplementary Fig. 6), which can capture more particles through hydrogen bonding, van der Waals forces, and dipole-dipole interactions, providing significant support for efficient filtration<sup>[15]</sup>. These zein-based membranes can be recycled and redissolved without significantly affecting their rheological properties, enabling the recycled production of biomimetic-fractal nanofibers (Fig. 1g) for good sustainability. Notably, the existing jet splitting process requires the forced introduction of ionic materials, which often become impurities and the content is difficult to control during recovery, making it difficult to reprocess. Fortunately, our strategy is based on well-volatile solvents, which make it easier to remove impurities and thus supporting reprocessing. Meanwhile, their mechanical properties and thermal stability show minimal decline after five reprocessing cycles (Supplementary Note 3 and Supplementary Fig. 7), ensuring good air filtration performance (It is presented in the section on air filtration test). Specifically, a total of 900 billion masks were consumed globally between 2020 and 2022<sup>[40]</sup>, which implies that the zein-based recycling strategy could save nearly 700 tons of zein raw material with a saving of at least \$100 million over three years (Supplementary Note 4) to reduce carbon emission of more than 6500 tons of CO<sub>2</sub> (Supplementary Note 5). In summary, commercial N95 masks have significant limitations (Supplementary Note 6) regarding breathing resistance (1.5 times higher), discomfort from heat (1.04 times higher) and moisture (1.2 times higher), and environmental impacts (proportion of plastic exceeds 95%)<sup>[40]</sup>, which reinforces the rationale and urgency for developing alternative mask materials. The actual wearing experience of the

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commercial N95 mask and our mask has been further evaluated to enhance the assessment of user-centric performance, showing that our mask has lower breathing resistance and better thermal comfort (Supplementary Note 7). Our mask maintains good filtration performance even after 50 cycles of wearing-removing, indicating durability (Supplementary Note 8).

### **Experimental Analysis Based on Conventional Parameters**

Experimentally, it is found that electrospinning parameters have the most critical impact on jet splitting and the formation of biomimetic-fractal fibers. The electrode-to-collector distance around 15 cm is effective for the full evaporation of the electrospinning jet by using the 8HAC/2ETOH or 8FA/2water as the solvent with zein at 31 wt%. The conductivity and viscosity of the 8HAC/2ETOH solution are 66  $\mu\text{S}/\text{cm}$  and 847  $\text{mPa}\cdot\text{s}$  and the jet splitting process only occurs at a high applied voltage of 26 kV and a low feed rate of 25  $\mu\text{L}/\text{h}$ . Reducing the applied voltage to 20 kV or increasing the feed rate to 200  $\mu\text{L}/\text{h}$  result in the jet to transition to a stretching state (Fig. 2a). On the other hand, by using 8FA/2water as the solvent, the conductivity and viscosity of solution are 1757  $\mu\text{S}/\text{cm}$  and 543  $\text{mPa}\cdot\text{s}$ , respectively, which are in favor of jet splitting process based on prior works for high conductivity and low viscosity. In contrary to the expectation, the jet electrospinning process consistently remains in the stretching state with fibers of uniformly distributed diameters (Supplementary Fig. 8a). Furthermore, experimental results are shown in Supplementary Fig. 8b-e by using 10HAC, 10FA, 5HAC/5ETOH, and 8HAC/2water as solvents with zein concentration at 31 wt%. In general, a high applied-voltage and a low feed rate help inducing the jet splitting process to specific solvents.

Supplementary Table 2 shows the jet behavior of 17 solutions with 31 wt% zein and the jet splitting and stretching process are found within the overlapping viscosity ranges of 241~1102 and 343~1875 mPa·s, respectively (Fig. 2b), without a consistent correlation. The conductivity factor also has no consistent correlation with jet behavior (Fig. 2c). On the other hand, the jet splitting and stretching process occurs for solutions with the surface tension in the range of 32.15~36.54 and 37.12~43.59 mN/m, respectively (Fig. 2d), with 37 mN/m as a key separation factor. By changing the concentration of zein between 27 to 33 wt%, the surface tension, viscosity, and conductivity of the solution with 10HAC as the solvent are 37.62 to 34.98 mN/m, 761 to 1549 mPa·s, and 39.5 to 38.2  $\mu$ S/cm, respectively. The increase in zein concentration leads to an increase in viscosity and a decrease in conductivity due to the hydrogen bonding effect. Even with a low conductivity and high viscosity, the 33 wt% zein solution successfully produces the jet splitting process to form biomimetic-fractal fibers as its low surface tension. Results for the 27 wt% zein show the stretching state in Fig. 2e due to the high surface tension. Similar results are found with 8HAC/2FA as the solvent (Supplementary Fig. 9). The impact of surface tension on the degree of jet splitting was investigated by adjusting the concentration of more solutions, as shown in Fig. 2f and Supplementary Fig. 10,11. In our previous works, the higher R-value indicated a more extreme bimodal distribution of fiber diameters, which can help determine the degree of jet splitting<sup>[23, 41]</sup>. Clearly, the lower the surface tension, the larger the R-value, indicating that the jet splitting was more intense (Supplementary Note 9).

### **Analysis of Jet Splitting Based on Simulation**

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To gain a deeper understanding of the hydrodynamic mechanisms behind jet splitting, simulation studies were further conducted. Based on experimental results, the role of surface tension was important and would be explored first. The initial electrospinning and solution parameters are shown in Supplementary Table 3. When the surface tension was 35 or 25 mN/m, the solution jet has only a single-peak state with the local electric field concentrate at a single tip. When the surface tension reduces to 15 mN/m, the solution jet goes into a fluctuating state with a complex and dispersed local electric field (Fig. 3a). By keeping the surface tension at 15 mN/m with a low applied-voltage (Supplementary Fig. 12a) or a high feed rate (Supplementary Fig. 12b), the solution jet is transformed into a single-peak state, which aligned with the conditions that could induce jet splitting in experiments. Further exploration of the entire jet flight process revealed that the jet with a surface tension of 25 mN/m consistently maintained a single-peak state throughout the stretching process (Fig. 3b). In stark contrast, the jet with a surface tension of 15 mN/m remains in a fluctuating state throughout the flight and eventually split (Fig. 3c), showing that the jet splitting is closely related to the fluctuations on the jet surface. Within the appropriate viscosity range ( $< 600 \text{ mPa}\cdot\text{s}$ ) that can form a jet, surface fluctuations always exist (Supplementary Fig. 13). Thus, the viscosity did not show any correlation with surface fluctuations, and no further investigation will be conducted.

Many prior works have explained the observed phenomenon as the very high electrical conductivity leads to excessive charge concentration at the jet tip to result in the electrostatic repulsion similar to that of the Coulomb explosion. Therefore, the effect of conductivity on the jet

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flight process was analyzed first. The surface tension was set to 15 mN/m, and other parameters, as shown in Supplementary Table 3, served as the control group. The liquid surface protrudes out at 2.4 ms without fluctuations and at 2.8 ms, the jet surface has significant fluctuations (Fig. 3d). By increasing the conductivity of the solution to 500  $\mu\text{S}/\text{cm}$ , the liquid level has no fluctuation at 2.4 ms, with a clear single tip under highly-concentrated local electric field. The single tip is later developed into a conical jet at 2.8 ms (Fig. 3e). By further increase the solution conductivity to 2000  $\mu\text{S}/\text{cm}$ , the jet splitting process still doesn't appear (Supplementary Fig. 14), showing that high conductivity failed to achieve the expected Coulomb explosion effect (Supplementary Note 10). In other words, the high conductivity allows ions to move quickly to the front region of the jet but did not result in extreme aggregation, forming a single conical tip and suppressing the jet fluctuations.

On the other hand, a self-pumping phenomenon (i.e., After stopping the solution supply for a period during electrospinning, the solution in the syringe will still spontaneously pump out completely) is observed in some solutions during the electrospinning process had led us to pay more attention to the role of relative permittivity (Supplementary Note 11 and Supplementary Fig. 15). By using a relative permittivity of 60 in simulations, the jet behavior is analyzed in Fig. 3f. The liquid surface exhibited noticeable fluctuations at 1.7 ms, which was significantly different from the control group and the high conductivity group (Supplementary Fig. 16). Obviously, a high relative permittivity is a key factor that causes interfacial fluctuations. This will be closely related to the strong dipole force since the conductivity remains constant. By 2.0 ms, the surface

had begun to form two peaks and a dispersed local electric field, with the fluctuations becoming more pronounced. Then, the jet transformed into a cone shape at 2.2 ms. In addition, the high relative permittivity resulted in shorter jet flight time and sharper cone (Supplementary Fig. 17), indicating that the dipole force could induce more effective electric field concentration to further accelerate and sharpen the jet. Analytically, the influence of free-charge force and dipole force on electrohydrodynamic behavior exhibits two key differences, including the form of interfacial fluctuations and the state of stress concentration. When a voltage is applied, there is a primary competition between surface tension ( $F_s$ ) and electrostatic forces, which can be further divided into classical electrostatic forces generated by free charge ( $F_I$ ) and dipole forces generated by dipoles ( $F_D$ ).  $F_I$  rely on the long-range movement and aggregation of free charge, while  $F_D$  only involve changes in dipole orientation. Therefore,  $F_D$  usually acts preferentially and dispersedly, forming a multi-tip disturbance at the liquid surface, while  $F_I$  tends to aggregate more widely and form a single tip (Fig. 3g). Moreover,  $F_D$  demonstrates stronger stress concentration, and when it dominates relative to  $F_s$ , it induces sharper jetting and flattens the jet surface (Fig. 3h). This situation was also supported when the surface tension of the control group was further reduced to 5 mN/m (Supplementary Fig. 18). Thus, the strong directional effect of dipole force has a greater impact on jet behavior than previously understood, and this will be further discussed.

### **Dipole-Oriented Electrospinning Model**

First, it can be clarified that the nature of jet splitting behavior is not a transient explosive behavior like Coulomb explosion, but rather an anisotropic stretching-tearing caused by the

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directional and strong stress concentration characteristics of dipole force. Moreover, based on the characteristics of dipole force, the jet splitting process can be reasonably explained, as shown in Fig. 4a. As long as there is an angle between the tangent of the jet surface and the direction of the electric field, new fluctuating points may form under the disturbance of dipole force, leading to anisotropic stretching and tearing.

To further validate the coupling mechanism between dipole force and surface tension, we focus on the relative permittivity, conductivity, and surface tension of the solution, and establish qualitative evaluation criteria for dipolar polarization effects (Supplementary Note 12). We construct solution systems (ECA and ECB) with similar and strong dipolar polarization effects (Supplementary Note 13 and Supplementary Fig. 19) but significantly different surface tension (Supplementary Note 14) while maintaining a very low conductivity about 15  $\mu\text{S}/\text{cm}$ . The solution parameters of the ECA and ECB are shown in Supplementary Table 4. Both the ECA and ECB solutions are well-dissolved and set at the same electrospinning parameters to ensure a stable electrospinning state (Supplementary Fig. 20). The ECA solution, characterized by strong dipolar effects and moderate surface tension, initially exhibits pronounced M-shaped interfacial fluctuations (Stage 1 in Fig. 4b). Subsequently, the two fluctuation points underwent anisotropic stretching and tearing (Stage 3 and 4 in Supplementary Fig. 21). Following this, secondary jets are formed at the inclined interface of the jet (Stage 2 and 3 in Fig. 4b). This process is repeatedly reproduced (Supplementary Fig. 21), eventually evolving into an extreme state of multiple secondary jet ejections (Stage 4 in Fig. 4b). The ECB solution, which had lower surface tension

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than the ECA solution, is initially shaped into a standard triangle due to the intense stress concentration from the strong dipole forces and is ejected normally. Subsequently, the inclined interface of the jet immediately undergoes splitting. Eventually, the solution at the nozzle is shaped into a spindle form and develops into an extreme anisotropic stretching (Fig. 4c and Supplementary Fig. 22). Clearly, the dipole force and surface tension have achieved the expected effects. Moreover, the ECA and ECB solutions experience 0.87 and 0.43 s, respectively, from the onset of jetting to the occurrence of extreme anisotropic stretching. It indicates that lower surface tension aids in the effectiveness of dipole effects, thereby enhancing jet splitting. Finally, we investigate the influence of the relative permittivity on several representative zein solutions discussed earlier (Supplementary Table 5), further supporting the conclusion that low surface tension and strong dipole effects jointly induce jet splitting.

The extreme importance of dipole effects in regulating jet behavior has been further explored.

The first aspect is inducing the jet splitting bucking the trend. By introducing a large amount of tea polyphenols (TP) with a high dipole moment of 4.73 debye (calculated using the density functional theory, as shown in Supplementary Fig. 23) into cellulose acetate (CA) and polymethyl methacrylate (PMMA) solutions, we significantly enhance the dipole effects (9.2 and 20.4 times respectively), induce jet splitting (Fig. 4d,e) under unfavorable conditions such as higher surface tension, lower voltage, and higher feed flow rates (Supplementary Note 15 and Supplementary Fig. 24), and successfully fabricate biomimetic-fractal nanofibers (Supplementary Fig. 25). This further facilitates energy savings and enhances manufacturing efficiency, thereby promoting the

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industrialized green manufacturing of more type biomimetic-fractal nanofibers.

The second aspect is determining the electrospinnability (Fig. 4f). As the voltage increases from 26 to 30 kV, the dipoles within both the ECA and ECB solutions quickly orient, leading to a reduction in the polarization gradient. The ECA solution, due to its higher surface tension, is difficult to deform, resulting in a nearly constant polarization gradient; thus, it remains in a taut but non-jetting state, gradually advancing forward, as shown in Supplementary Fig. 26 and solid box in Fig. 4f. In contrast, the lower surface tension of the ECB solution allows the tip to form more easily, which enhances the polarization gradient. This is followed by jetting, where the polarized solution is stretched forward as a whole. At this moment, the inclined interface experienced splitting, and the overall gradient of the jet formed, restoring the normal spinnable state, as shown in Supplementary Fig. 27 and dashed box in Fig. 4f. The ECC solution is further constructed to have a slightly lower surface tension than the ECA solution, along with a reduced dipole effect (Supplementary Note 16 and Supplementary Fig. 28). Unsurprisingly, the ECC solution can continuously grow protrusions but was unable to jet properly (Supplementary Fig. 29). It is worth noting that for solutions with strong dipole effect, this non-spinnable state may be quite common. The stronger the dipole effect, the lower the voltage required to achieve complete polarization, which leads to non-spinnability. When the voltage required for spinnability exceeds expectations for the electrospinning process window, many formulations may be mistakenly considered unspinnable, which could significantly hinder the development of new materials.

The third aspect is shaping the ribbon jet. When the dipole effect is strong, the jet is prone to

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exhibit a planar distribution of stress points, similar to using two hands to pull out a sheet of paper, resulting in a flatter sheet (Supplementary Fig. 30). Additionally, the high surface tension, lacking any opposing force, will compress the jet. Ultimately, this causes the PMMA/TP solution to form wide and flat ribbon-like fibers (Fig. 4g).

For high conductivity solutions, jet splitting cannot be effectively achieved based on Coulomb explosion. On one hand, existing research suggests that charged droplets may release charges through air ionization<sup>[42]</sup>. On the other hand, the highly dynamic jetting process of electrospinning is also unfavorable for charge accumulation. It should be emphasized that the prevailing strategy for inducing jet splitting behavior currently involves the addition of ionic materials. While their primary purpose is to enhance solution conductivity, certain formulations may also prove effective, largely due to the high dipole moments of many ionic materials. However, for certain easily ionizable solution systems, the dipole effects can be completely disrupted, and in such cases, even a significant increase in conductivity will not induce jet splitting. Therefore, without clarifying the importance of dipole effects, it will be challenging to effectively regulate electrospinning jet behavior, and material matching may become misleading. These further highlight the significance of this study.

### **Air Filtration Test**

The biomimetic-fractal nanofibrous membrane fabricated by electrospinning from 33 wt% zein solution has utilized for air filtration applications due to its relatively low average diameter and distinct biomimetic-fractal structures. At an air flow rate of 32 L/min, when the basis weights

of the zein biomimetic-fractal nanofibrous membranes are 0.15, 0.3, 0.45, 0.6, and 0.75 g/m<sup>2</sup>, the corresponding filtration efficiencies are 79.63%, 97.17%, 99.81%, 99.97%, and 99.995%, with pressure drops was 19.7, 38.5, 56.2, 77.3, and 95.3 Pa (Fig. 5a). The increase in basis weight led to the increase in fiber packing density for improved filtration efficiency and increased pressure drop. On the other hand, when the basis weight increases from 0.15 to 0.75 g/m<sup>2</sup>, the quality factor (QF) first increases from 0.081 to 0.111 Pa<sup>-1</sup> and then decreases to 0.104 Pa<sup>-1</sup> (Fig. 5b). The QF of the zein biomimetic-fractal nanofibrous membrane is consistently higher than that of the core layer of the N95 mask, indicating its excellent air filtration performance due to the optimized structure. However, the excessive increase in basis weight led to overly dense fiber accumulation, making it difficult to balance filtration efficiency and pressure drop to result in a decline in the air filtration performance<sup>[43]</sup>. Due to the best air filtration performance, the zein biomimetic-fractal nanofibrous membrane with a basis weight of 0.45 g/m<sup>2</sup> is used for subsequent testing and compared with the core layer of N95 mask.

The air filtration performance at different air flow rates is investigated. When the air flow rate increases from 16 to 85 L/min, the filtration efficiency of the zein membrane decreases slightly from 99.95% to 99.71%, while the filtration efficiency of the N95 mask core layer decreases significantly from 98.11% to 95.42% with lower QF, as shown in Fig. 5c and Supplementary Fig. 31a,b. This indicates that the zein membranes have good mechanical filtration capabilities, with a more stable filtration effect under high wind speeds, whereas the core layer of the N95 mask core layer relied on electrostatic adsorption, making it difficult to maintain stable filtration under high

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wind speeds<sup>[34]</sup>. The upward trend of the pressure drop under different air flow rates conforms to the Darcy's law, indicating the effectiveness of the test. The air filtration performance is further explored under different relative humidity. When the humidity increases from 50% to 90%, the filtration efficiency of the zein membrane only slightly decreases from 99.81% to 99.76%, while the filtration efficiency of the N95 mask core layer significantly drops from 97.08% to 92.98% (Fig. 5d). Obviously, high humidity caused charges to dissipate more easily<sup>[44]</sup>, which significantly degrades the electrostatic adsorption capability of the N95 mask core layer, but it has almost no effect on the zein membrane. Furthermore, the increase in humidity did not significantly affect the pressure drop of the N95 mask core layer due to its strong hydrophobicity. However, the pressure drop of the zein membrane increases under high humidity (Supplementary Fig. 31c) because of its hygroscopicity. Nonetheless, the QF of the zein membrane remained above  $0.09 \text{ Pa}^{-1}$ , which is significantly higher than that of the N95 mask core layer (Supplementary Fig. 31d). A 120-minute loading air filtration experiment is conducted. The filtration efficiency of the zein membrane remains above 99.8%, indicating that it has good mechanical filtration ability to achieve stable filtration efficiency (Fig. 5e). However, the filtration efficiency of the N95 mask core layer significantly decreases to 92.92%, which is attributed to the electrostatic charge shielding caused by the particulate matter. Due to its excellent mechanical filtration performance, the zein membrane could continuously capture more particles, while the pressure drop increased from 56.2 to 80.2 Pa. In contrast, the particle capture ability of the N95 mask core layer is not as good, and the pressure drop only slightly increases from 59.2 to 62.1 Pa (Supplementary Fig. 31e). Despite

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the significant increase in pressure drop, the QF of the zein membrane remains above  $0.08 \text{ Pa}^{-1}$ , which is much higher than that of the N95 mask core layer (Supplementary Fig. 31f). Therefore, the zein membrane exhibited good and stable air filtration performance, capable of functioning in harsh conditions such as high wind speeds and humidity. The air filtration mechanism of the bimodal structure is also analyzed. Due to the slip effect, the air flow lines will be closer to the fine fiber surface. Ultrafine particles undergo intense Brownian motion around the air flow lines to collide with fine fibers more easily and deposit on the surface (Fig. 5f). On the other hand, coarse particles will move along the air flow line and be intercepted by the pores of the membrane (Fig. 5g). Most importantly, the combination of the coarse and fine fibers will prevent a sharp increase in the pressure drop, thereby demonstrating better air filtration performance.

The actual filtration effect of the zein membrane is tested in a cigarettes smoke test. After filtration, the surface of the fiber membrane captures a large amount of oily particulate matter and exhibits a sticky state, while it still maintains a clear biomimetic-fractal structure (Fig. 5h). This indicates the feasibility of the zein membrane in practical filtration applications. Finally, due to the pure composition of the zein membrane, it can be easily recycled and remade into a biomimetic-fractal structure. After 5 reprocessing processes, the QF of the zein membrane can still maintain above  $0.1 \text{ Pa}^{-1}$  (Fig. 5i and Supplementary Fig. 32), demonstrating good recyclability for the development of sustainability. To better reflect real-world conditions, additional testing with oily particles is performed by replacing NaCl with diethylhexyl sebacate (DEHS). When the air flow rate is  $32 \text{ L/min}$ , the filtration efficiency, pressure drop, and QF of the zein membrane are

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(99.68±0.02)%, (56.9±0.5) Pa, and (0.101±0.001) Pa<sup>-1</sup>, respectively, while for the N95 mask core layer, the filtration efficiency, pressure drop, and QF are (93.27±0.35)%, (59.5±0.2) Pa, and (0.045±0.001) Pa<sup>-1</sup>, respectively (Data are reported as their means ± SDs from  $n = 5$ ). Clearly, the weak polarity of oily particles makes it difficult for the electrostatic adsorption effect of the N95 mask core layer to function effectively, while the physical barrier of the zein membrane remains effective. Moreover, the filtration efficiency for PM<sub>0.3</sub> is a scientific, rigorous, and conservative core performance indicator. It serves as the foundation for global mainstream protection standards (e.g., N95, KN95, and FFP2) and effectively reflects the material's physical barrier capability against bioaerosols, including viruses. Therefore, the zein membrane exhibits good filtration performance for both saline and oily PM<sub>0.3</sub>, covering most types of harmful aerosols encountered in real-world environments.

## Discussion

This study presents a dipole-oriented electrospinning model, revealing the fluid mechanics behind the jet splitting behavior, specifically the formation of multiple fluctuation points at the jet interface and its anisotropic stretching-tearing. Strong dipole effect and low surface tension are key factors inducing jet splitting behaviors, which typically occur at the inclined interface of the jet. Compared to classical free-charge force, dipole force can induce a stronger stress concentration effect, which is a significant factor in the formation of multiple fluctuation points at the jet interface. Furthermore, dipole effect is closely linked to broader jet behaviors, including jet weakness and

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ribbon-like stretching. Excessively strong dipole effect can lead to rapid orientation of dipoles within the jet, weakening the polarization gradient and resulting in non-spinnability; strong dipole effect combined with high surface tension led to extreme uneven forces on the jet, forming wide and flat ribbon-like jets. Unfortunately, the relative permittivity, closely related to dipole effect, has received little attention in electrospinning studies. While conductivity is a widely explored key parameter in electrospinning, its effect is not as anticipated, as jet splitting behavior is not solely caused by high conductivity. Ultimately, by specifically reducing the surface tension of the solution, jet splitting of pure zein solution was achieved, successfully producing zein biomimetic fractal nanofiber membranes that can be assembled into lightweight masks. The venation-like structure allows the membrane to achieve high-performance air filtration with a QF greater than  $0.1 \text{ Pa}^{-1}$  at  $0.45 \text{ g/m}^2$ , which not only reduces material usage by over 50% but also facilitates the dissipation of exhaled heat, enhancing wearing comfort. Additionally, the homemade masks exhibit good transparency, allowing for clear recognition of facial expressions during wear, thus promoting safer social interactions and human-machine interactions. Most importantly, due to the purity of the components, the produced nanofiber membranes can be easily recycled and reprocessed, maintaining good air filtration performance with a QF consistently above  $0.1 \text{ Pa}^{-1}$  even after five processing cycles, greatly promoting sustainability.

This study still has some limitations that require further in-depth research in the future. Firstly, the application depth is still limited, particularly regarding the skin irritability of masks during actual wear. More clinical experiments are needed in the future to further enhance user-centered

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performance evaluation. Secondly, the lack of systematic exploration of bioaerosol filtration leaves the actual protective efficacy and safety of masks in complex and dynamic real-world biological environments not fully assured. Thirdly, the current preparation of the zein biomimetic-fractal membrane depends on high voltage and low feed flow rates, leading to increased energy consumption and insufficient production efficiency. There is an urgent need to achieve the decoupling of multiple parameters and to develop a jet-splitting behavior directional enhancement strategy under low voltage and high feed flow rates. Fourthly, the coordination of jet-splitting behavior, membrane structure, and final performance is essential. Specifically, at the microscopic level, precise prediction and regulation of jet dynamics should be achieved; at the mesoscopic level, quantitative characterization and directional construction of the multi-level structure of the fiber membrane should be completed; and at the macroscopic level, a multidimensional performance evaluation system oriented towards applications should be established, ultimately bridging the quantifiable and predictable mapping relationships among the three.

## **Methods**

### **Materials**

Zein ( $M_w \approx 26,000$ , purity 95 %) powder was purchased by Shanghai Titan Technology Co. Ltd. (China). Ethyl cellulose (EC,  $M_w \approx 130,000$ ) and vanillin were all purchased from Shanghai Yuanye Bio-Technology Co. Ltd. (China). CA (acetyl group 39.8 wt%, viscosity 38 P), PMMA (flow-injection type), menthone, curcumin (purity > 98 %), and citronellal were all obtained from Shanghai Aladdin Biochem Technology Co. Ltd. (China). TP (purity > 97 %) was purchased from

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Macklin Biochemical Technology Co., Ltd. (China). Formic acid (FA), *N,N*-dimethylformamide (DMF), ethanol (ETOH), dimethyl sulfoxide (DMSO) were all obtained from Sinopharm Chemical Reagent Co. Ltd. (China). Acetic acid (HAC) was purchased by Xilong Scientific Co. Ltd. (China). Deionized water was obtained from Boer Chemical Reagent Co. Ltd. (China).

### **Preparation of Electrospun Fibrous Membrane**

The zein powder was directly added to specific solvents, stirred for 6 h until completely dissolved, and then used immediately. All the solutions were prepared for immediate use. The solution was named based on the concentration of zein and the composition of the solvent. For example, 8FA/2HAC indicates that the solvent system was composed of a blend of 80% FA and 20% HAC by volume. Furthermore, under the given solution conditions, 32 wt% zein represents a zein concentration of 32 wt%. All solutions were electrospun using an electrospinning equipment (NL-E-ES-2, Xiamen Narai Technology Co. Ltd, China). The environmental temperature and relative humidity were controlled at  $25\pm 2$  °C and  $50\pm 3\%$ , respectively. The electrospinning distance was controlled at 15 cm. The needle model was 25 G. Unless otherwise specified, the applied voltage and flow rate are defaulted to 26 kV and 25  $\mu$ L/h, respectively.

### **Characterization**

The conductivity and viscosity of the solution were determined at 25 °C using a conductivity meter (DDS-307A, INESA Scientific Instrument Co. Ltd, China) and a rotational viscometer (NDJ-8S, Bangxi Instrument Technology Co. Ltd, China), respectively. The relative permittivity was measured using a relative permittivity tester (LJD-2878, Beijing Zhonghang Dingli

Instrument Equipment Co. Ltd., China) at 25 °C and 70% RH over a frequency range of 20 Hz to 1000 kHz with a constant AC voltage of 1 V. The surface tension was measured using a drop shape analyzer (ZJ-7000, Shenzhen Zhijia Instrument Equipment Co. Ltd., China) based on the sessile drop method. Fiber morphology was examined using scanning electron microscopy (SEM; SUPRA 55 SAPPHIRE, Carl Zeiss AG, Germany). The diameters of at least 500 fibers were analyzed with ImageJ. To assess temperature variations on the outer surface of masks during the respiratory cycle, an infrared thermal imager (E09pro, Hikvision Co. Ltd, China) was utilized. A UV/Visible/Near-Infrared spectrophotometer (LAMBDA 1050+, PerkinElmer, USA) equipped with an integrating sphere was used to measure the transmittance in 380–780 nm (visible light). The weight and thickness of various samples were measured using a precision electronic balance (BSA124S, Sartorius, Germany) and an electronic thickness gauge (A1, Shenzhen Yuanhengtong Co. Ltd., China), respectively. A high-speed digital camera (M110, Vision Research Corporation, America) was used to capture the electrospinning jet at a frame rate of 1500 fps.

### **Simulation of Electrospinning Jet Behaviors**

The electrospinning jet behaviors has been simulated by using finite element method, as shown in Supplementary Fig. 33. The establishment of the Taylor cone model is as follows: a capillary tube was vertically positioned, filled with a polymer melt at its entrance. An electric field existed outside the tube, allowing the liquid to move upward under the influence of the electric field, overcoming gravity, and ultimately forming a Taylor cone. To reduce computational load and enhance efficiency, the entire model was a two-dimensional axisymmetric representation. Fluid

flow was simulated using a computational fluid dynamics (CFD) two-phase flow level set approach with a moving mesh interface (one phase being the polymer solution and the other phase being air), while the electric field was modeled through an electrostatic interface and introduced via the Maxwell stress tensor. In the electrostatic physics interface, the negative electrode was grounded, and a non-zero voltage was applied to the positive electrode at the entrance of the capillary tube. To improve convergence in the calculations, the study type was selected as transient with phase field initialization. The relevant fluid parameter settings are shown in Table S3. In order to improve computational precision, the mesh partitioning method was conventional triangular mesh P3 discretization.

### **Air Filtration Test**

The air filtration performance of the electrospun nanofibrous membranes was evaluated by measuring the filtration efficiency for 0.3  $\mu\text{m}$  NaCl aerosol particles alongside the pressure drop. Additional testing with oily particles is performed by replacing NaCl with DEHS. Both parameters were assessed using an air filter comprehensive performance tester (LZC-K1, Suzhou Huada Co. Ltd., China). The testing area was 100  $\text{cm}^2$ . The default air flow rate was 32 L/min, corresponding to a wind speed of 5.3 cm/s.

The QF serves as a measure of the overall performance, indicating that a higher QF corresponds to good air filtration efficiency. It was calculated using the Eq. (1):

$$\text{QF (Pa}^{-1}\text{)} = -\frac{\ln(1-\eta)}{\Delta p}, \quad (1)$$

where  $\eta$  represents the removal efficiency determined using a laser particle counter, while  $\Delta p$  denotes the pressure drop recorded by a pressure transmitter.

### Data Availability

The data that support the findings of this study are available within the article and its supplementary files. Any additional requests can be requested from the corresponding author.

Source data are provided with this paper.

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### **Author Contributions Statement**

Z. Shao conceived and designed the research, carried out the experiments, analyzed data, and wrote the manuscript. Y. Liu, S. Huo analyzed data and assisted in the characterization. Q. Zhang, J. Chen, H. Chen, B. Wang, Z. Xu, Y. Chang assisted in the characterization. S. Zhong, G. Zheng, L. Lin conceived the research, supervised the project and modified the manuscript. All authors discussed the results and reviewed the manuscript.

### **Competing Interests**

The authors declare no competing interests.

### **Figure Legends/Captions (for main text figures)**

#### **Fig. 1: Jet-splitting formation and characteristics of zein fractal nanofibers.**

**a** (left) Zein is the principal protein of corn; (right) typical jet splitting or stretching behavior after the electrospinning process. **b** (left) Fractal geometry in nature and biomimetic-fractal fibers

fabricated by electrospinning process; (right) dipole-oriented jet splitting mechanism. **c** Image of three prototype zein membranes of 2, 1, and 0.45 g/m<sup>2</sup> on top of the Xiamen University logo. **d** A prototype face mask based on 0.45 g/m<sup>2</sup> zein membrane and its wearing effect. **e** Infrared transmittance and water vapor transmittance rate (WVTR) for different masks. **f** Infrared images when wearing different masks. **g** Recovery process of defective samples and its economic benefits based on statistics of global mask consumption from 2020 to 2022. Data in **e** are reported as their means  $\pm$  SDs from  $n = 5$ , and source data are provided as a Source Data file.

**Fig. 2: Experimental analysis of electrospinning jet behavior and fiber morphology.**

**a** Jet behavior and fiber morphology of 31 wt% zein solution with 8HAC/2ETOH as solvent under different electrospinning parameters. Electrospinning parameters corresponding to different jet behaviors: **b** viscosity; **c** conductivity; **d** surface tension. **e** Jet behavior and fiber morphology of 27 wt% and 33 wt% zein solutions (10HAC as solvent). **f** Surface tension (ST) for solutions of 10HAC as solvent with 29, 31, and 33 wt% zein, as well as accordingly fiber morphology (scale: 2  $\mu$ m), R-value (represents degree of jet splitting), and diameter distribution (Da represents average diameter). Data in (**b**, **c**, **d**) are reported as their means  $\pm$  SDs from  $n = 5$ , and source data are provided in Source Data file and Supplementary Table 2. Data in **f** are reported from  $n = 200$ , and source data are provided in Source Data file.

**Fig. 3: Simulation Results and Electrohydrodynamic Behavior Analysis.**

**a** Jet behavior and electrostatic forces acting on it under different surface tension (ST). Jet volume

fraction during flight when surface tension is: **b** 25 mN/m; **c** 15 mN/m. Jet behavior and electrostatic forces acting on it under different conditions: **d** surface tension is 15 mN/m, other conditions are shown in Supplementary Table 3, and this group is used as the control group; **e** conductivity of control group is raised to 500  $\mu\text{S}/\text{cm}$ ; **f** relative permittivity of control group is raised to 60. Schematic diagrams of electrohydrodynamic behavior induced by dipole force ( $F_D$ ) and free charge force ( $F_I$ ): **g** interface fluctuation; **h** stress concentration.  $F_s$  represents surface tension.

**Fig. 4: Evolution and analysis of jet splitting behavior.**

**a** Schematic diagram of the jet splitting process based on dipole orientation, featuring an anisotropic stretching-tearing jet. Electrospinning process at 26 kV, 20  $\mu\text{L}/\text{h}$ , 15 cm: **b** ECA solution; **c** ECB solution. Solution images and electrospinning results at 20 kV, 50  $\mu\text{L}/\text{h}$ , 15 cm: **d** CA and CA/TP solutions; **e** PMMA and PMMA/TP solutions. **f** Electrospinning results at 30 kV, 20  $\mu\text{L}/\text{h}$ , 15 cm of ECA solution (solid box) and ECB solution (dashed box). **g** Electrospinning results at 30 kV, 50  $\mu\text{L}/\text{h}$ , 15 cm of PMMA/TP solution.  $F_D$  and  $F_s$  present dipole force and surface tension, respectively.

**Fig. 5: Test results of air filtration performance.**

Results of zein biomimetic-fractal nanofibrous membranes with different basis weight: **a** filtration efficiency and pressure drop; **b** quality factor. Air filtration efficiency at different: **c** air flow rates; **d** relative humidity; **e** testing time. Schematic diagram of filtering mechanism: **f** ultrafine particles;

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**g** coarse particles. **h** Fiber morphology of biomimetic-fractal nanofibrous membrane before and after filtration. **i** Filtration performance of zein biomimetic-fractal nanofibrous membrane after multiple recycling and reconstruction. Data in (**a**, **b**, **c**, **d**, **i**) are reported as their means  $\pm$  SDs from  $n = 5$ , and source data are provided in Source Data file. Data in **e** is sampled at one-minute intervals, and source data are provided in Source Data file.

**Editorial summary:** Designing zein-based face air filters are promising, though it is challenging to balance air filtration and optical properties. Here the authors use a jet-splitting method to fabricate a transparent face mask, maintaining air filtration properties.

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