Executive Summary

Water is an invaluable resource for sustaining all forms of life and drives the intricate ecosystems that support human civilization. As we confront challenges such as population growth, climate change, environmental pollution, and over-extraction, water shortage has become one of the most severe crises that threaten biodiversity and sustainable human development. Desalination of salty water (seawater or brackish water) and reclamation of municipal wastewater have emerged as crucial strategies in addressing the challenge of water scarcity.

Reverse osmosis (RO) desalination is a water purification technology that removes salt and other impurities from seawater or brackish water to produce fresh and drinkable water by overcoming the osmotic pressure using a semipermeable membrane. *RO desalination currently constitutes 2/3 of the world's installed desalination capacity,* but it suffers from two challenges right now: (1) high operational pressures and (2) membrane fouling. High operational pressure increases energy consumption and operational costs. Membrane fouling diminishes the efficiency of the RO system, decreases water production rates, and reduces the membrane service lifetime. Therefore, it is crucial to reduce operational pressure and minimize fouling to achieve energy-efficient desalination while maintaining optimal purification performance.

In this proposal, an innovative design of topological spacers is proposed to overcome the challenges arising from the RO desalination process. Although the current flat-structure spacer has been used to promote turbulence in the feed flow patterns to enhance the cross-flow flux, the improvement is still very limited. The proposed topological spacers with a bio-mimic topology could offer a breakthrough for boosting water desalination performance at reduced energy consumption and minimized membrane fouling. 3D printing provides a perfect way to implement the design of such intricate topologic geometry, which is difficult for traditional molding processes. Consequently, reducing the energy consumption of RO desalination also reduces the carbon footprint, promotes environmental conservation, and mitigates the effects of climate change on water resources. Furthermore, the adoption of this novel spacer design can have significant social sustainability impacts and implications for social acceptability. The proposed solution could make RO desalination more energy-efficient and improve the membrane service lifetime by minimizing membrane fouling, thus making clean and drinkable water more accessible and affordable, particularly in regions facing water scarcity or contamination issues. The implementation of this design can create more economic opportunities by supporting agricultural activities, promoting local industries, and creating more job opportunities, leading to improved socio-economic conditions for communities. Reduced carbon footprint and decreased reliance on traditional water sources will address water-related health challenges in communities and protect water-related ecosystems.

1. Industry Overview

Rapid population growth (1% growth rate per year) and industrialization have made freshwater shortage one of the most severe crises that threaten human beings. Currently, about 4 billion people suffer from the scarcity of drinkable water at least one month per year. Freshwater resources, mostly in the form of groundwater and surface water, only account for 1% of the total water resources on earth[1, 2]. This freshwater is not only necessary for maintaining human life but also essential for social development, such as agriculture, aquaculture, and power generation. For example, one important water management strategy in Texas is the desalination of brackish water present in the Texas aquifers to meet the demand of the increasing population.

Reverse osmosis (RO) membrane-based water desalination technology has attracted significant attention and accounts for two-thirds of the world's installed desalination capacity to produce drinkable water[3]. The commercial RO desalination process is illustrated in Figure 1. The primary barriers hindering the broader adoption of RO desalination technology are the high energy and infrastructure expenses. Therefore, substantial endeavors are required to improve the energy efficiency of RO desalination while maintaining its purification performance. RO membrane fouling is another challenging issue, and it significantly increases the feed operation pressure, resulting in much higher energy consumption. The membrane fouling also significantly increases the maintenance cost, shortens the membrane service lifetime, and reduces the purification performance.

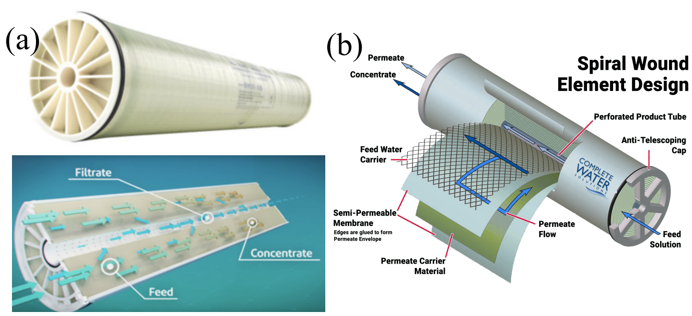

Figure 1. (a) Illustration of water desalination in the commercial RO module. (b) The spacer is used in the RO module [3].

Numerous attempts have been made to tackle such challenges, but the challenges remain unresolved. For example, some novel nanostructure membranes promise to acquire high water flux and high salt-rejection rates at low energy consumption, but the difficulty in scalable production hinders their industrial applications. Besides the membrane, the feed spacer plays a critical role in the industrial RO water desalination process, where a feed spacer is placed together with the RO membrane to promote turbulence in the feed flow pattern (Figure 1b)[4]. It is widely acknowledged that feed-feed spacer geometries have a vital impact on the hydraulic characteristics and anti-fouling behavior of membrane modules[5]. So far, many attempts have been made to investigate the geometric configuration effect on the flow characteristics and system performance. For example, hexagonal patterns and rectangular patterns were found to be more efficient in promoting local turbulent flow than the commercial diamond patterns in the spacer, demonstrating >30% higher water flux at the same feed operational pressure and, thus, 30% more energy-efficient[6]. Many other simulation efforts have been made to incorporate a variety of geometric configurations to tune the energy efficiency and improve the anti-fouling capability[2]. However, **it seems most of these efforts have been focused on the flow pattern design and optimization.** In contrast, there are relatively few efforts focused on designing and optimizing the topology of the feed spacer. Apart from the considerations of energy efficiency, the fouling in RO desalination has been a haunting problem for all RO processes. Although it has been lessened, it remains unresolved. The frequent backwashing of the RO membrane and even replacement substantially increase the maintenance expenses and impede water accessibility.

The expected timeline is listed in Table 1:

Table 1. Timeline of the proposed design and manufacturing plan

	1-week	1-week	1-week	1-week	1-week
Simulation and 3D model revision					
Material supply and facility preparation					
Printing and quality control					
Surface coating					
Test					

2. Design, Functionality and Durability

To address the challenges of energy efficiency and fouling in the RO modules, a bio-mimic feed spacer with a gill raker-like topology structure is proposed to simultaneously promote local turbulent flow for higher energy efficiency and prevent fouling agents from sticking to the RO membrane. The enhanced antifouling capability is projected to result in a substantial reduction in energy consumption and a significantly prolonged service lifetime of the RO member. The quantitative improvement will be identified by the tests.

The fish gill raker structure is shown in Figure 2. Briefly, an array of rakers with different heights stays above the gill filament, which is similar to the RO membrane. The array of rakers creates localized turbulent flow and prevents any particles from clogging the gill filament.

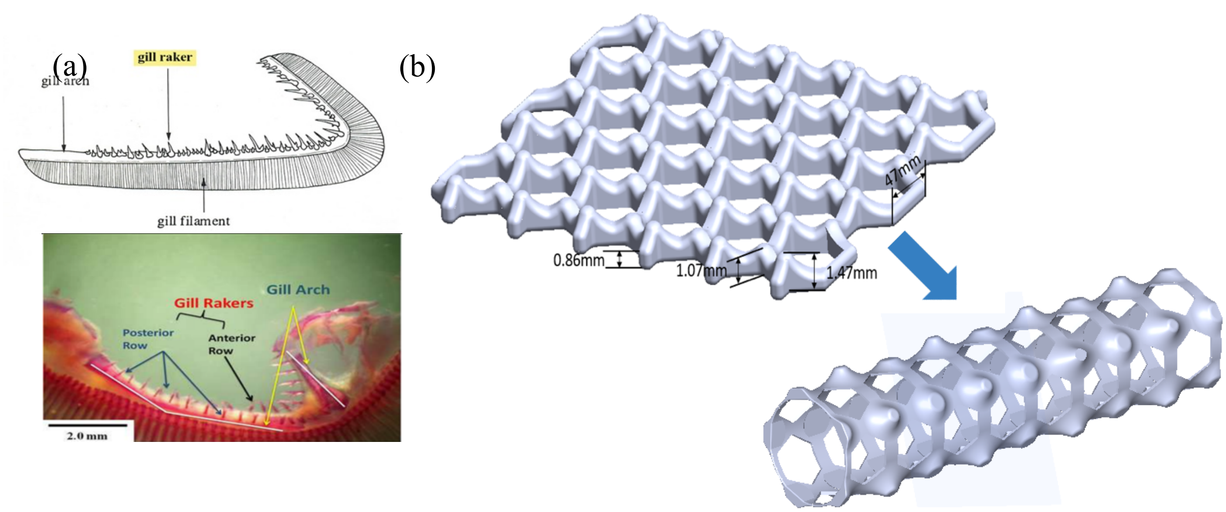

Figure 2. (a) Scheme and optical image of the fish gill raker structure[7] and (b) the proposed biomimetic spacer structure with wave-like array topology and hexagon pattern. The spacer can also be wrapped into a cylinder to fit a RO module.

Inspired by fish gill raker structures and functionality, The gill raker-mimic spacer with a wave-like topology is shown in Figure 2(b). The base thickness is 0.86mm according to the industrial standard. Each lattice of the honeycomb base is cylindrical to promote the water flow with minimized pressure drop. The height of the “raker” is 1.47mm and 1.07mm in an alternative order. This kind of biomimetic spacer is expected to promote localized turbulent flow, which could reduce energy consumption for higher water flux, and locally suspend the fouling agents to significantly reduce the membrane fouling. The local flow has been simulated using commercial COMSOL Multiphysics software, shown in Figure 3.

The simulation diameter is 7.9”, and the flow length is 40”, according to the industrial standard RO unit. For the proposed biomimetic spacer, localized turbulent flow was observed, with complex flow direction and a fast flow rate(1.2X locally faster due to as-designed spacer topology) compared to a commercial spacer. Therefore, using a biomimetic spacer is anticipated to improve energy efficiency and significantly hinder membrane fouling through localized turbulent follow. The preliminary results of numerical modeling indicated that the simulated fish gill raker structure could facilitate to suspend >89% of particles, significantly reducing the fouling possibility.

The as-designed spacer will follow all the industry standards with no health or safety concerns. They will be highly durable, and their lifetime is expected to be more than 5 years.

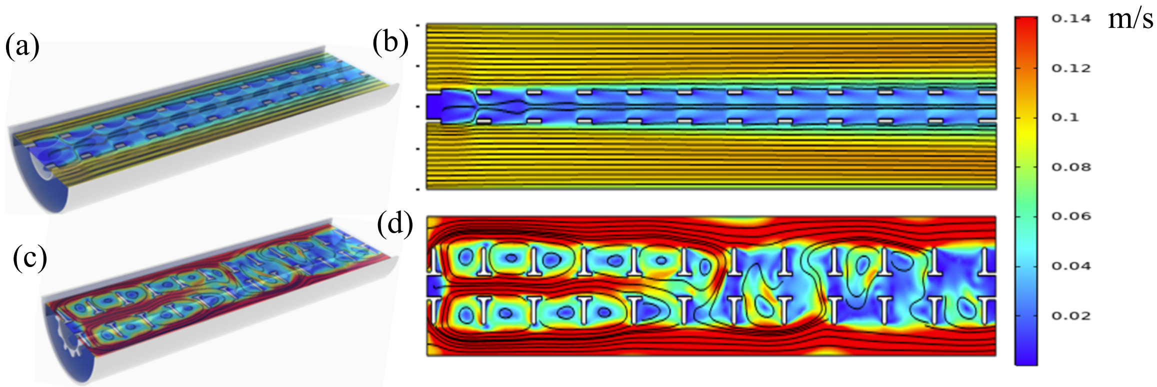

Figure 3. COMSOL Multiphysics simulation of 3D water flow (left) and their top view (right). (a) and (b) are the control, (c) and (d) incorporate the as-designed spacer into the RO module.

3. Design Integration and utilization of DDM materials and processes

The as-designed biomimicking spacer shows a honeycomb base with cylindrical lattices and an array of “gill-raker” like cones with 2 different heights, promoting wave-like localized turbulent flow. This novel geometrical configuration will be fabricated through digital manufacturing since it might be difficult for traditional processes. For example, it will be difficult to do traditional thermoforming, injection molding, or extrusion.

To choose the right materials for 3D printing, the first thing is to identify the right 3D printing methods for this design since there are many different 3D printing approaches, ranging from selective laser sintering (SLS), fused deposition model (FDM), direct energy deposition (DED), continuous liquid interface production (CLIP), and digital light processing (DLP). Considering the cost, plastics should be the top choice. Usually, the photo-curable polymer is not chemically resistant and not hydrophobic, and thus, DLP-based 3D printing is usually not a good choice. Currently, many commercial spacers in the RO module are made from polyethylene (PE) due to their chemical resistance, durability, and flexibility. It can withstand harsh conditions within an RO module. PE filaments with different grades are commercially available and provide a good way to print the as-designed spacer using the FDM process. Therefore, the FDM printing process will be chosen to showcase this design using PE filament as the raw material. Compared to traditional manufacturing, the availability of the filament should be critical.

The biomimicking topology can significantly reduce the scale fouling, while the biofouling and organic fouling need further improvement. To further improve the spacer's anti-fouling performance, the printed spacer will be coated with a mixture of graphene/ZnO/ Polyvinylidene Fluoride (PVDF) by traditional dip-coating. The PVDF could further enhance the spacer's chemical resistance, while graphene can help break down various biofouling agents[8, 9]. ZnO can also create radicals to degrade organic fouling[10]. Therefore, a combination of 3D printing and traditional surface coating will be showcased to produce a highly flexible and durable spacer with outstanding antifouling capability.

Considering the 3D printing process and the subsequent dip-coating, the as-designed spacer can also be printed by DLP, followed by surface coating for chemical resistance and hydrophobicity. The final surface coating significantly extends the potential printing method beyond the typical FDM. With a follow-up of traditional coating, the as-designed part can be adapted to many other 3D printing methods, like DLP and CLIP, etc.

4. Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean, and continuous improvement

To disseminate the design, the CAD/CAM drawings and the COMSOL Multiphysics modeling results will be posted on social media, like LinkedIn, Facebook, and Twitter. The design rationale and process can also be illustrated in an animation video and uploaded to the YouTube website. Any potential feedback and discussion will facilitate the dissemination of the novel design.

To coordinate the manufacturing, the first issue is the whole dimension of the spacer parts; for example, one of the commercial spacers is size 7.9” by 40”. The capability of the FDM instrument has to be verified. The FDM instrument must be capable of printing a large-size part. Secondly, raw material supplies must be identified, too. The source, size, and grade of the filament need to be provided. In large corporations, manufacturing is usually coordinated internally due to sufficient internal resources, infrastructure, and expertise. They typically can organize an internal team to ensure the in-house manufacturing is efficient and timely. The service bureaus, also known as contract manufacturers, or third-party manufacturing firms, typically provide manufacturing services to businesses and individuals on a contract basis. Their manufacturing is typically managed by project managers who liaise with clients to understand their requirements, coordinate production schedules, and ensure quality control. For hobbyist makers, small-scale manufacturers may not have the resources of large corporations or service bureaus. They can leverage tools like 3D printers, CNC routers, and other desktop manufacturing equipment to produce small batches or prototypes. Manufacturing involves managing supply chains for raw materials, coordinating production schedules, and ensuring quality control within their capacity.

To enable the resiliency of the supply chain, the following issues are important:

Diversification of Suppliers: Instead of relying solely on a single supplier for critical components or materials, the design/manufacturing plan can incorporate multiple suppliers. This diversification reduces the risk of disruptions due to supplier failures, geopolitical issues, natural disasters, or other unforeseen events.

Supplier Relationship Management: Establishing strong relationships with suppliers and maintaining open communication channels can facilitate collaboration, risk-sharing, and problem-solving. The design/manufacturing plan can include provisions for regular supplier assessments, performance evaluations, and contingency planning.

Inventory Management: Balancing inventory levels and lead times is crucial for mitigating supply chain disruptions. The design/manufacturing plan can incorporate strategies such as buffer stock, safety stock, and just-in-time (JIT) inventory management to ensure adequate inventory levels while minimizing excess inventory costs.

Technology Integration: Leveraging technology such as data analytics, real-time monitoring, and predictive modeling can provide insights into supply chain dynamics and enable proactive decision-making. The design/manufacturing plan can incorporate technology solutions that enhance visibility, traceability, and collaboration across the supply chain.

5. Cost Benefit/Value Analysis

The proposed design is anticipated to reduce energy consumption by >30% and also extend the lifetime of the RO membrane by >20%, estimated according to the COMSOL simulation. For example, currently, in the Texas Water Desalination Plant located at El Paso, the annual energy cost in RO desalination is ~\$2M, where \$1.4M/year is contributed by the membrane filtration process (others are contributed by pre-treatment and disinfection processes). Therefore, using the proposed spacer for RO membrane can cut down the energy cost contributed by the membrane filtration process from \$1.4M to \$0.98M or lower per year. As a result, the total energy cost for RO desalination at El Paso can be reduced from the current \$2M/year to \$1.58M/year, which is about a 0.4M/year reduction in total energy costs!

In addition, a further decrease in fouling could reduce maintenance by at least 20%. It also significantly extends the lifetime of the RO membrane.

The downside of the new spacer might be the current slow manufacturing rate of 3D printing compared to traditional processes like injection molding. 3D printing usually has a lower production rate than traditional processes, such as injection molding. A cost comparison between injection molding and 3D printing is shown in Figure 4[11]. For a small volume production < 500, 3D printing is more beneficial to the process, while injection molding is much cheaper if >500 units are produced. In this case, it is reasonable to assume the production volume is much more than 500 units, and thus, the spacer cost could be a little more expensive than the traditional counterpart. However, considering the lifetime of the spacer, ~7 years, and the energy saving and reduced cost from the membrane, the benefits of using the new design are extremely attractive.

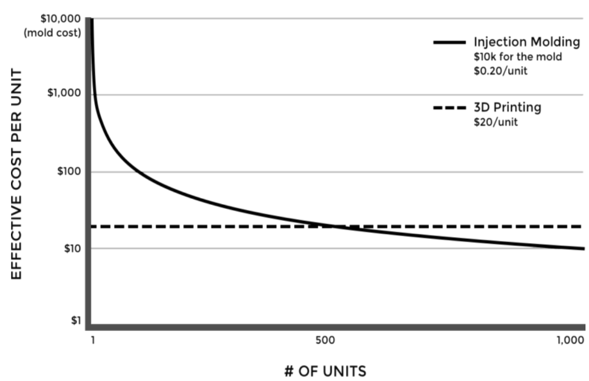

Figure 4. Compare the cost of 3D printing and injection molding[11].

Further advancement of new 3D printing technology may reshape this kind of manufacturing cost. For example, the part that needed 11.5 hours to fabricate by SLA may only need 6.5 minutes(~100X faster) to fabricate using emerging CLIP technology, which was invented in 2015 and is in commercialization now[12, 13]. We expect the manufacturing rate of 3D printing to be competitive with traditional injection molding in the near future. Therefore, 3D printing could provide versatile geometry configuration and also a fast production rate.

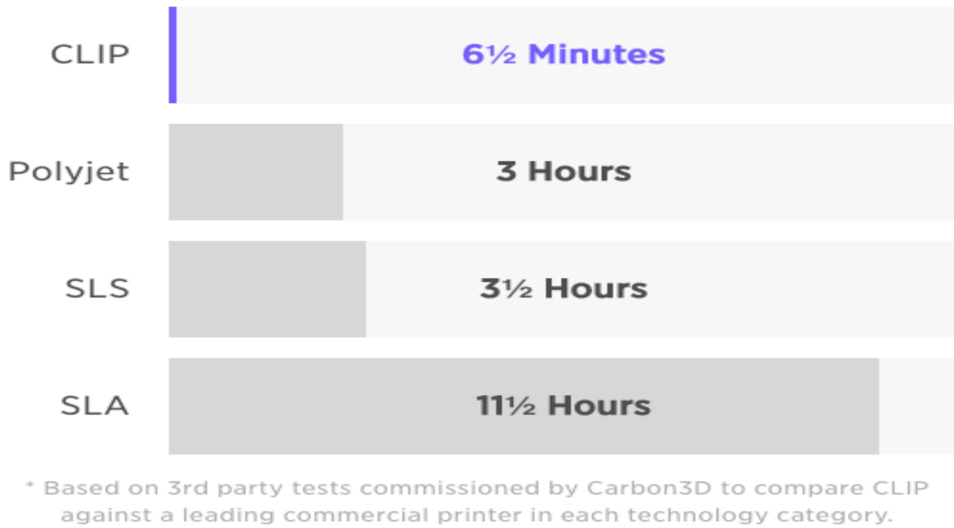

Figure 5. Progress of the 3D printing production rate[12]

6. Conclusions

In conclusion, a bio-mimic spacer of RO desalination has been designed, and COMSOL simulation indicated it could reduce both energy consumption and fouling significantly. It can be printed by FDM with PE filament and followed by surface coating to further boost the anti-fouling capability. The innovation of this design is a fish gill-raker mimic spacer for the RO module. This represents a pioneering effort to develop a feed spacer inspired by gill rakers for the RO module, demonstrating both topological and geometric innovations to promote local turbulent flow and effectively combat various forms of fouling. The design and manufacturing plan could accelerate RO desalination practices and enhance the accessibility of fresh water, impacting both daily life and various industrial activities that significantly demand water.

7. Reference list

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