Shrimp Happens: Engineering a Polyculture Recirculating Aquaculture System (RAS)

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Background

Shrimp are the most consumed seafood item in the US, and although the Gulf of Mexico supports a successful fishery, only 15% of the US shrimp market is domestically sourced.[1] The US is the world's largest seafood importer, which has created a $20.3 billion trade deficit.[2] In 2023, 30% of this deficit was from shrimp imports alone.[2] Most of our imported shrimp comes from intensive or semi-intensive farms in Asia. These imports drive down the cost of domestic wild-caught shrimp. To close this trade gap and meet the growing demand for local seafood, there is a continuing effort to bolster the US aquaculture industry, including intensive shrimp farming.

Polyculture, Integrated Multi-trophic aquaculture (IMTA), and aquaponics are all sustainable aquaculture methods that are becoming increasingly popular with the growing demand for sustainable seafood. Shrimp have been successfully farmed with species of *Gracilaria* (algae) and *Salicornia (*halophyte plants). These existing systems informed the design of a polyculture RAS to produce shrimp and seaweed for restaurants in New Hampshire.

Target Species: *Litopanaeus vannamei*[3]; *Gracilaria tikvihiae; Salicornia bigelovii*[4]

Objectives

- Design a modular, fully functional RAS that produces 5-10*kg* of Whiteleg shrimp (*Litopanaeus vannamei*) in 3-6 months
- Incorporate *Gracilaria* spp. and *Salicornia* spp. into the RAS to improve water quality and serve as additional marketable products
- Develop a financial plan to demonstrate how the RAS can be scaled to produce shrimp and seaweed at a commercial scale

Bio-plan

- Calculations of growth rate, production of waste, and consumption of oxygen
- Designed for harvest day when waste production and oxygen consumption will be highest
- Projected growth rate was inferred from Zeigler Bros Inc. feed prediction tool

Waste Production and Oxygen Consumption

- TAN and TSS : $P = (Rate_{feed})(\frac{kg\ Protein}{kg\ Feed})(\frac{kg\ X}{kg\ Protein})$
- Oxygen: $P = (Rate_{feed})(\frac{mg\ O_2}{kg\ Feed})$
- Carbon Dioxide : $P = (Rate_{feed})(\frac{mg\ O_2}{kg\ Feed})(\frac{mg\ CO_2}{mg\ O_2})$

Required Flow Rate

- Equation: $Q = \frac{P}{(C_1 - C_2)}$
- The flow rate for each product was calculated, and the largest of the flow rates was used as the "required flow rate"

Table 1: Key values calculated for main system using governing equations and metrics from existing shrimp systems in the literature.

Parameter	Final Value
Feed Rate	0.05 (kg feed/kg shrimp)
TAN Production	1.27 (mg/min)
TSS Production	82.76 (mg/min)
O_2 Production	275.87 (mg/min)
CO_2 Production	200 (mg/min)
Required Flow Rate	61.30 (L/min)

System Design

MAIN SYSTEM

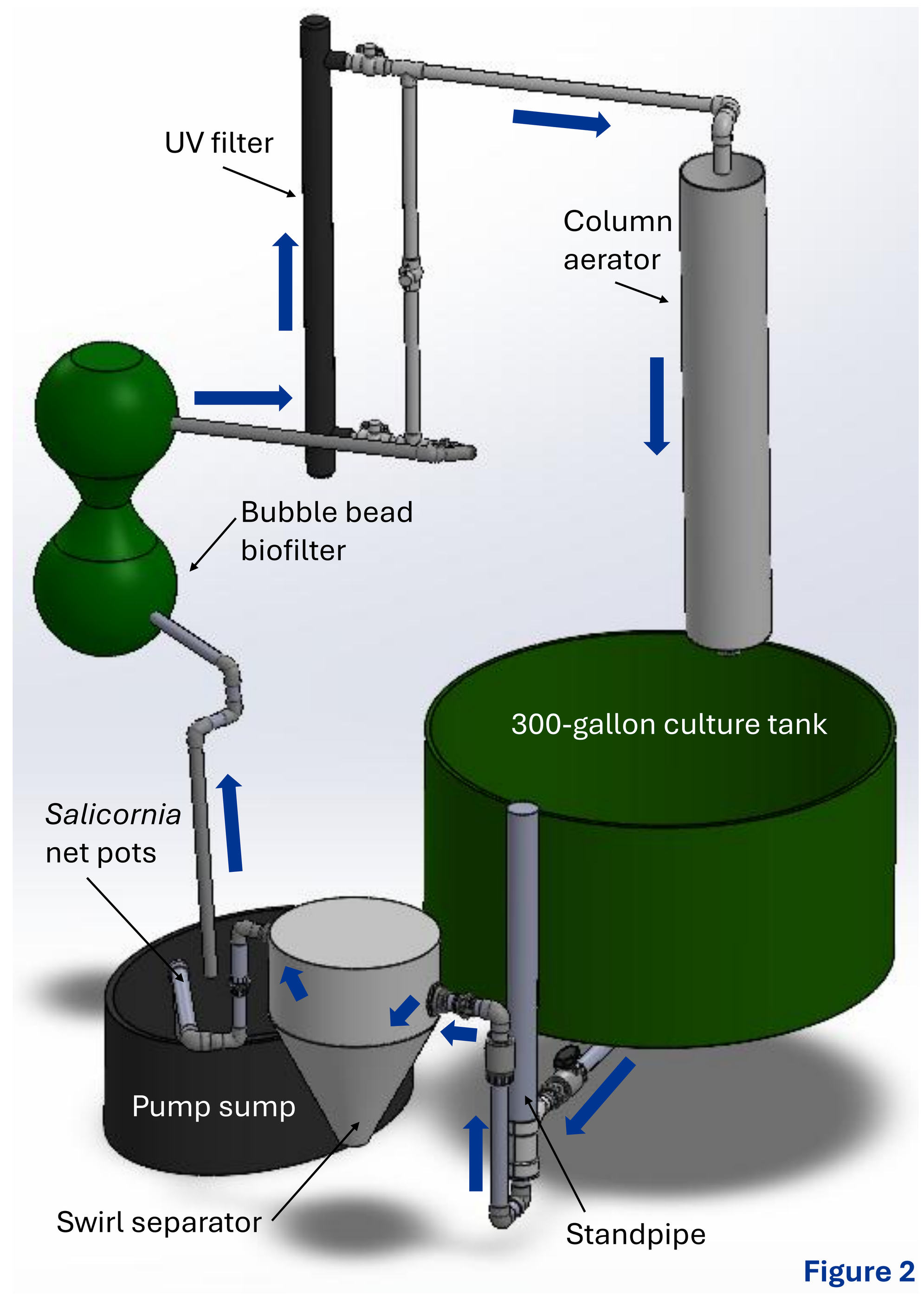

Figure 2

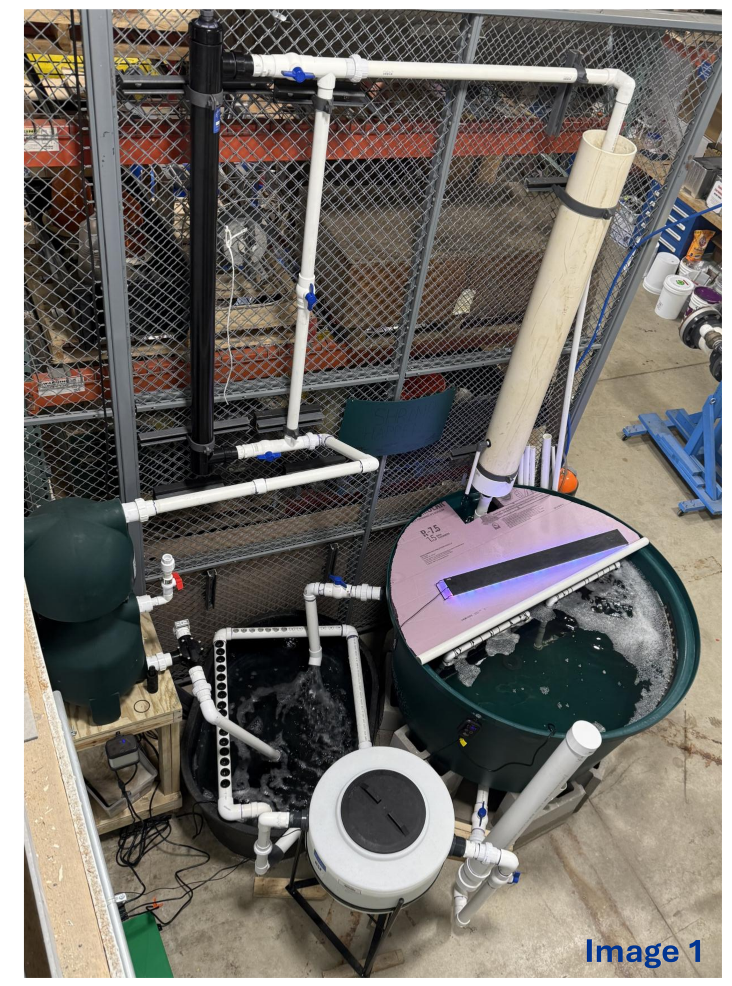

Figure 2: SolidWorks was used to construct a model of the main system to scale. Major parts are labeled and blue arrows represent the direction of water flow.

Image 1: A bird's eye view of the fully operational main system. All components are modular, so the system can be rebuilt in any location.

NURSERY SYSTEM

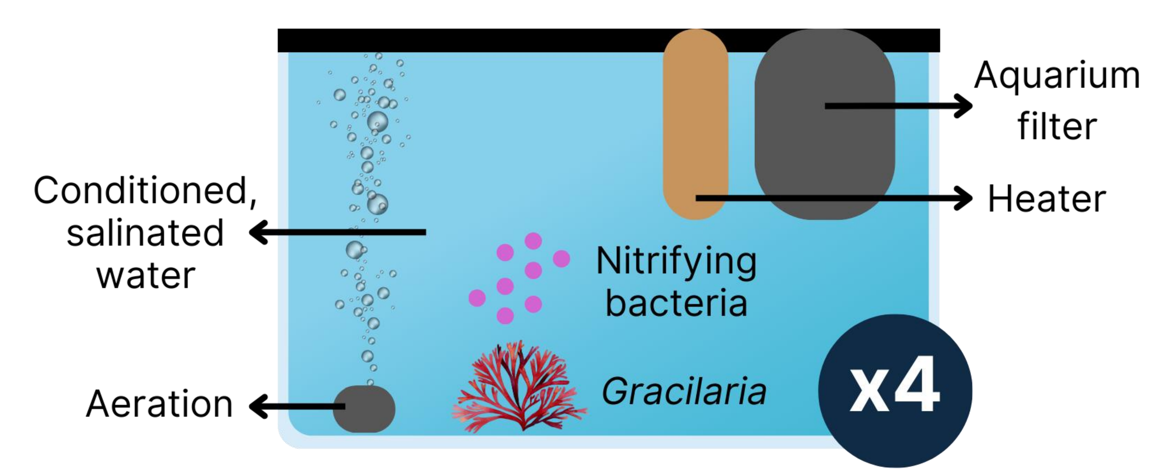

Figure 3: The nursery system contains all the essential components of the main system and is used to allow small post-larval (PL) shrimp to grow out to a size at which they will be more resilient. All tanks were wrapped in insulating material to reduce heat loss. Our shrimp were PL20 and spent two weeks in the nursery. Shrimp can spend between 1-4 weeks in this system before being transferred to the main system.

SPECIES SELECTION AND INTRODUCTION

Image 2: PL20 shrimp were obtained from Miami Aqua-culture Inc. and placed in the nursery system to grow out for two weeks before being added to the main system. Shrimp were fed four times a day with feed containing 49% crude protein to encourage rapid growth.

Image 3: *Gracilaria* spp. were collected from Great Bay estuary to be incorporated into the main system. The algae was intertwined in thin mesh on PVC panels and hung vertically from the center of the culture tank through the water column. *Gracilaria* uses nitrogenous wastes from the shrimp to grow and helps eliminate harmful ammonia.

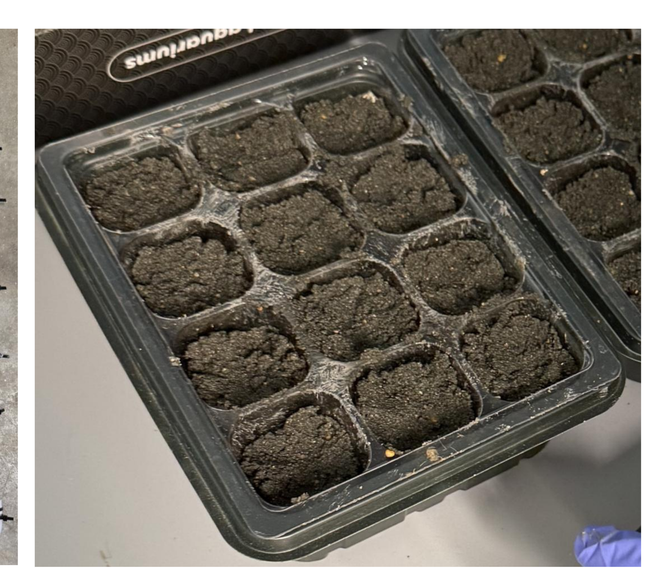

Image 4: *Salicornia bigelovii* seeds were obtained from a USDA seed bank and planted in a 25% mud, 75% sand mixture. This species has never been successfully germinated from a seed in an artificial environment, so wild collection should be explored instead.

Component Selection

Component	Governing Equation	Discussion
Culture Tank	Ideal Diameter to Depth Ratio $2:1 - 4.5:1$	Based on the stocking density of shrimp and including the volume used by Gracilaria, a 1.14m^3 tank with a diameter to depth ratio of 2:1 was chosen.
Swirl Separator Variables: V = Volume Q = Flowrate A_b = Area of basin	Hydraulic Retention Time $HRT = \frac{V}{Q}$ Hydraulic Loading Rate $HLR = \frac{Q}{A_b}$	Based on the required flow rate, HLR, and HRT for waste to be separated a 0.11m^3 swirl separator was chosen. It's dimensions yielded a HRT of 1.75min and HLR of 222.07$\frac{lpm}{m^2}$.
Sump Variables: d_p= Particle diameter ρ_p = Particle density ρ_w = Density of Water μ = Dynamic Viscosity g = Gravitational constant	Particle Settling Velocity $v_s = \frac{g d_p^2(\rho_p - \rho_w)}{18\mu} = \frac{Q}{A_b}$	Using the required flow rate and particle settling velocity, the minimum required volume of the basin was 0.57m^3. To satisfy this, a tank with a volume of 0.57m^3 was used.
Pump Variables: h_f= Frictional losses h_m= Minor losses h_s= Static losses	Head Loss $HL_{total} = h_f + h_m + hs = \left(f\frac{L}{D}\frac{v^2}{2g}\right) + \left(K\frac{v^2}{2g}\right) + (H_{st}H_{su})$	The head loss of the system was 12*m* but to account for the flow rate and allow for modularity, a pump designed for *18.5m* of head was used.
Bubble Bead Filter	Bead Media Required $V_{media} = \frac{Rate_{feed}}{Feed\ Load}$	Based on the appropriate feed rate and load, 0.04m^3 of media area required. A bubble bead filter with a media volume of 0.06m^3 was used.
UV Filter Variables: Q_{filter}= Filter max flowrate D_{filter}= Filter rated dosage Q_{req}= required flowrate D_{req}= required dosage	Dosage $Q_{filter}D_{filter} = Q_{req}D_{req}$	The UV filter selection was based on the required flow rate and the dosage needed to kill bacteria in the system. A UV filter supplying a dosage of 151.96$\frac{mj}{cm^2}$ was chosen.
Column Aerator Variables: P = Power ρ = Density of water g = Gravitational constant h = Column height Q = System flowrate C= Oxygenation Capacity	Water Power $P = \rho g h Q$ Oxygen Replenishing Rate $Rate_{o2} = PC$	The size of the column aerator was based on the required oxygen replenishing rate, determined in the bio-plan. A 1.7*m* long column was used to achieve this level of oxygenation.

Conclusion

- Polyculture RAS can be a sustainable way to introduce a local shrimp source to NH seacoast restaurants
- *Gracilaria* spp. are effective at removing harmful ammonia from shrimp culture tank
- 12 systems 3.3x the size of the prototype system would produce enough shrimp for a local restaurant (5,400 kg/year)

Future Directions

- Collect and integrate *Salicornia* spp. into system
- Facilitate reliance on solar energy to provide 4.817 GWh of electricity annually
- Scale production for restaurant sales by expanding system
- Develop stronger community outreach programs around sustainable aquaculture for schools using main system as a model system

References and Acknowledgements

[1] Asche, F., Oglend, A., & Smith, M. D. (2022). Global markets and the commons: The role of imports in the US wild-caught shrimp market. *Environmental Research Letters*, *17*(4), 045023. https://doi.org/10.1088/1748-9326/ac5b3e.
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[3] https://www.inaturalist.org/taxa/1071972-Penaeus-vannamei
[4] https://www.flickr.com/photos/30928455@N02/2896851732/

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