Sustainable and Total Recovery of Resources (Energy, Clean Water, and Fertilizers) from Wastewaters through the Anaerobic Membrane Bioreactor Platform

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Energy positive and sustainable wastewater treatment through Anaerobic Membrane Bioreactors (AnMBRs) with simultaneous recovery of valuable nutrients (Nitrogen, Phosphorus) and water for indirect potable reuse is emerging as a viable option for municipalities, agro-businesses, and other utilities. A pilot scale AnMBR operated by the PI's team at Ft. Riley, Kansas, under ambient conditions continuously for 270 days treating 1000 gallons per day of municipal wastewater has consistently achieved these goals. Specifically, this AnMBR process configuration was able to achieve approximately 73% energy neutral operation by maximizing gaseous and dissolved methane energy capture while minimizing gas sparging and mixing energy requirements. The AnMBR also achieved an average removal efficiency of 88±7% and 88±6% for COD and BOD_5, respectively, at temperatures ranging from 12.7°C to 31.5°C, demonstrating its feasibility for ambient temperature operation. The AnMBR was also paired with downstream nutrient recovery using a coagulation-flocculation-sedimentation process, removing 94±3% of phosphorus and over 99% of nitrogen, as well as both gaseous and dissolved methane capture, which could generate an estimated 72.8% of the power required for energy neutrality. The successful integration of AnMBRs in a treatment train that addresses the critical challenges of dissolved methane and nutrients demonstrates the viability of the technology in achieving holistic wastewater treatment.

Background

While several wastewater treatment facilities have been able to achieve energy neutral operation through limited carbon (mainly methane) and nutrient (struvite alone) sequestration options, the need to enhance digested biosolids quality while decreasing the quantity and high capital/operation costs remain challenges that limit widespread adoption of these platforms.

Anaerobic membrane bioreactors (AnMBRs) are an emerging environmental biotechnology platform that can address these challenges by enabling efficient anaerobic treatment along with volatile solids reduction, tailored and separate sequestration of high-quality ammonia and phosphorus, and significantly lower biosolids production.[1,2] In addition to the benefits conferred by anaerobic technologies, the use of membranes enables AnMBRs to be a low-footprint technology that can effectively operate at longer solids retention times (SRT) by decoupling hydraulic retention time (HRT) and SRT for the treatment of high organic loads, and produce high-quality effluent amenable to reuse.[3-6] However, the introduction of membranes necessitates fouling control measures that can consume up to 50% of the total energy demand and increase chemical use.[7-12] While the pairing of membranes with anaerobic treatment represents an advancement, it still falls short of accomplishing holistic treatment. An alternative option, proven at the bench-scale by author Parameswaran, combines energy, nutrient, and water recovery from municipal wastewater with significantly lower net energy requirements (0.11 KWh/m^3)

compared to the conventional activated sludge-based wastewater treatment (0.49 KWh/m^3).[13]

Feasibility

AnMBRs are an emerging environmental biotechnology with greatest potential to enable agricultural, industrial, and municipal waste treatment to achieve simultaneous, energy-positive treatment and valuable recovery of water for reuse and nutrient products.[14-16] Concentrated waste streams such as animal wastes and food wastes should yield greater value proposition through AnMBR operation due to the higher organic load, based on preliminary TEA analyses.[17] It is important to note that little to no research has focused on beneficial nutrient recovery from wastewaters in an AnMBR platform through the coagulation/flocculation or other recovery platforms.

The system operated by the author's team is one of the largest pilot AnMBRs in the world (Figure 1) and has demonstrated successful operation on municipal wastewater to produce treated water meeting ANSI reuse standards (BOD_5 ◎ 10 mg/L) under ambient temperatures for more than a year, with an HRT of around 6 hours.[18-22] The level of fecal coliforms in the treated water was below detection during the continuous operation. As pointed earlier, this pilot system provides the basis for process innovation, modification, and system integration for various configurations.

Moreover, AnMBR research has demonstrated that the ability to achieve energy-positive treatment increases as the Organic Loading Rates (OLRs) increase, often at values greater than 4.5 kg COD/kg VS m^{-3}, as occurs with animal wastewater.[23-25] AnMBR as a sustainable wastewater treatment platform was supported by the EPA through a project, in partnership with the Department of Defense through the ESTCP program [Project Number: ER-201434 – Anaerobic Membrane Bioreactor (AnMBR) for sustainable wastewater treatment], in which Drs. Prathap Parameswaran and Stacy Hutchinson were investigators on this project, which was one of the proud recipients of the 2019 ESTCP Project of the Year award.

Results from this project demonstrate the ability of the AnMBR platform to achieve superior treatment of the municipal wastewater as demonstrated by the effluent COD/BOD_5 values under ambient temperature conditions, which even meets ANSI reuse standards. A separate coagulation-flocculation system downstream of the AnMBR enabled superior nutrient capture efficiency (NH_4-N > 98% and PO_4-P >90%), while meeting strin-

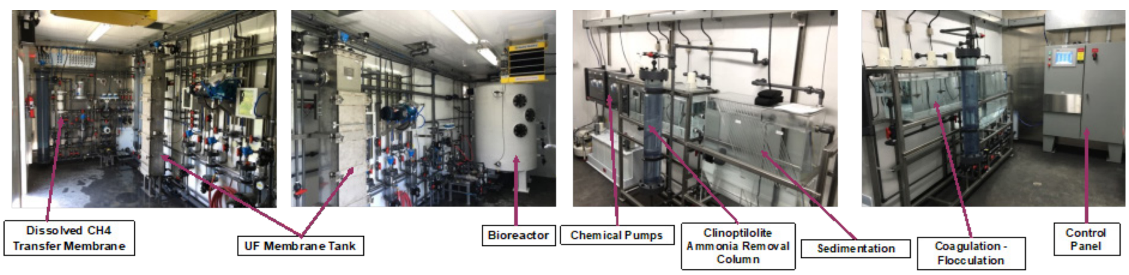


Figure 1. Schematic of the pilot-scale AnMBR (from left to right) located at the K-State animal farm to be used for this study, showing the gaseous and dissolved-methane capture from the primary and gas-sparged membrane bioreactor, coagulation-flocculation process for phosphorus recovery and clinoptilolite ion-exchange resin for ammonia capture, from municipal wastewater. The system will be available for carrying out the proposed research.

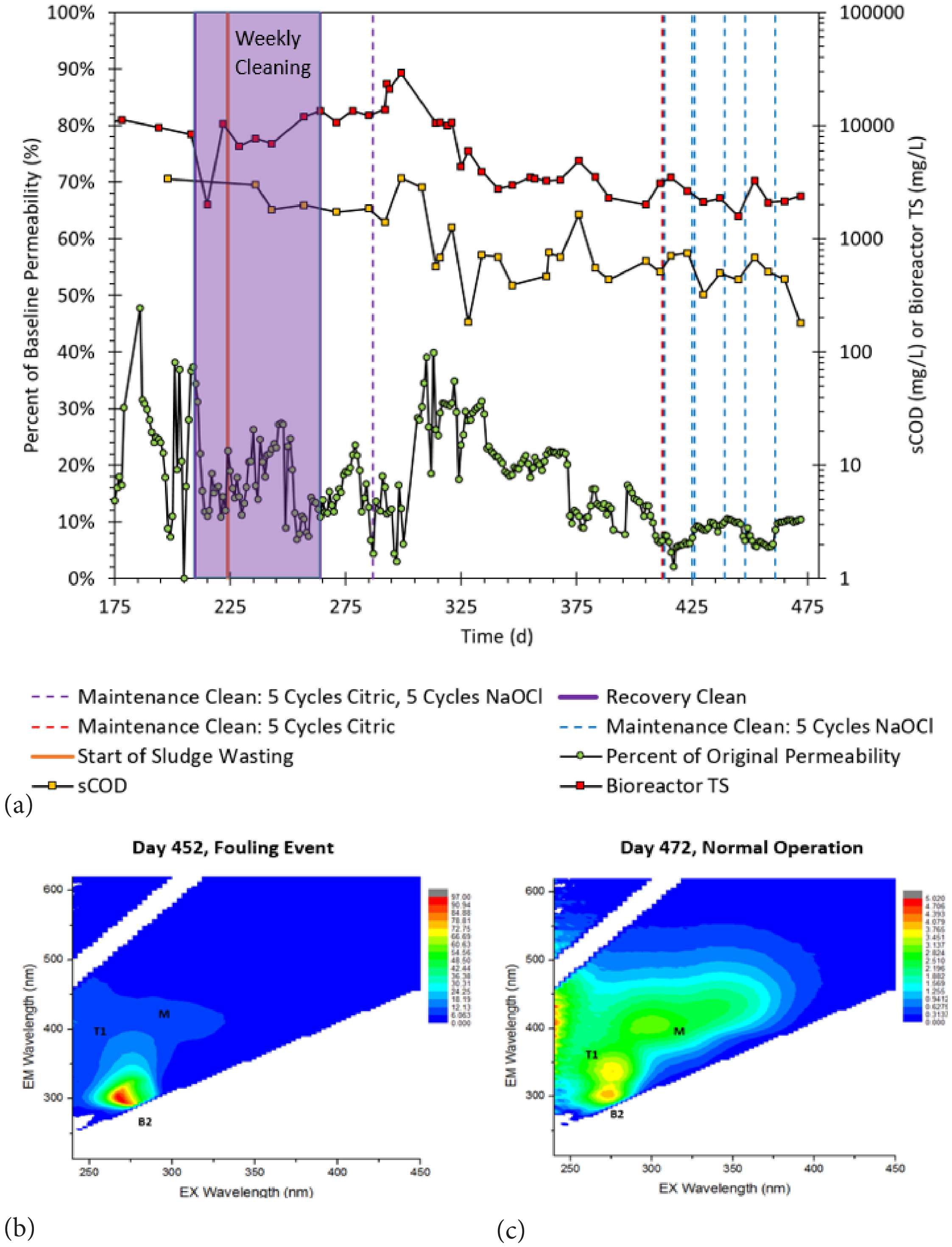


Figure 2. (a) Membrane permeability a function of cleaning events in pilot scale AnMBR. Specific interest from days 278 to 420 without membrane cleans (b) EEMS profile during fouling event and (c) EEMs profile during normal operation.

gent effluent nutrient standards for N and P to produce output water superior to conventional municipal wastewater treatment.[13]

Proactive and targeted membrane fouling management on electrode and membrane surfaces

Membrane fouling is a critical factor for successful AnMBR operation. The pilot scale gas sparged AnMBR operation on dilute wastewater revealed that while maintenance cleaning was effective initially, its ability to restore permeability decreased with time. Wasting bioreactor solids appeared to be effective in restoring permeability where chemical cleans were unable to.[26] The restoration mechanism appears to be associated with a **decrease in colloidal material**, measured by semi-soluble chemical oxygen demand (ssCOD), rather than bioreactor total solids concentration (Figure 2A).

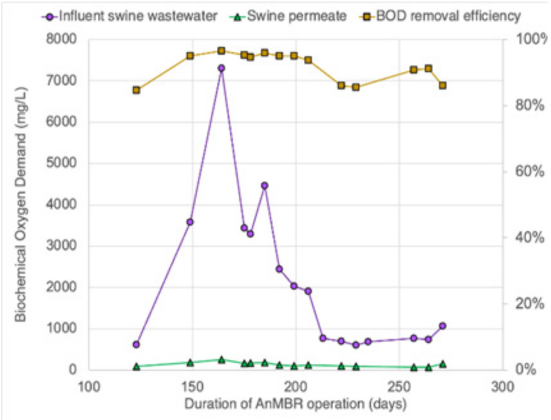
This was further supported through the use of fluorometry during AnMBR operation, which showed an increase in tyrosine-like compounds during heavy fouling conditions, suggesting that proteinaceous materials have a large influence on fouling (Figures 2B and 2C).

This was corroborated during membrane autopsy using Fourier Transform Infrared Spectroscopy (FTIR, data not shown). FTIR, scanning electron microscopy with energy dispersive x-ray spectroscopy, and transmission electron microscopy were used to characterize inorganic scalants and predominantly found phosphate salts and calcium sulfate. Fundamentally characterizing foulants and introducing novel and dynamic monitoring parameters during AnMBR operation such as ssCOD and fluorometry can enable more targeted fouling control, **leading to significant savings in fouling management expenditure and downtime**.[27] Extended periods of pilot-scale gas sparged AnMBR operation without maintenance cleaning due to **proactive monitoring of colloidal COD and commensurate solids wasting** is shown in Figure 2A.

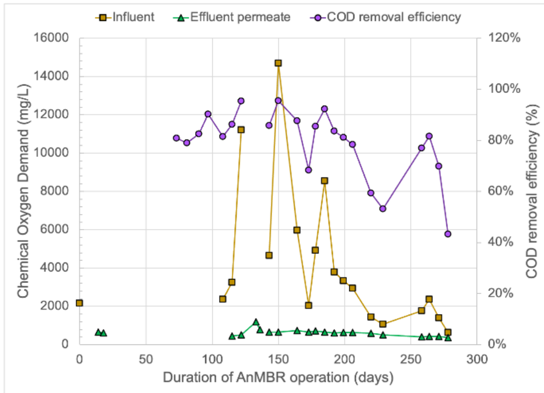
Suitability of AnMBRs for resource recovery from animal waste slurry – Preliminary Results

The author's team has been operating a lab-scale AnMBR unit, described in prior publications, with swine lagoon wastewater as the primary waste fed, for about 350 days. The swine waste was collected from a swine lagoon input pipe located in the Swine Teaching and Research Unit at Kansas State University's north farm. After a startup phase of about 100 days, key process parameters that indicate successful treatment were initiated. The health and stability of the membranes were continuously monitored by tracking the TMP during the production cycles. ***Successful average COD (>80%) and BOD$_5$ (~95%) removals were achieved during steady state operation*** between 150 and 270 days, shown in Figure 3. It is to be noted that the COD removal efficiency responded more strongly to the influent COD fluctuations, compared to the BOD removal efficiency. This likely indicated that the biodegradable fraction was effectively being metabolized by the anaerobic consortia, while the recalcitrant organics were being removed primarily by membrane filtration. COD and BOD$_5$ removals were accompanied by commensurate generation of biogas. The headspace biogas composition revealed an average methane content of around 62 ±8% in the headspace, indicating a robust anaerobic environment. This is one of the first long-term demonstrations of superior organics removal from a swine lagoon waste.

Matching with the organics removal, **the AnMBR permeate also achieved superior removal of indicator bacterial pathogens (total and fecal coliforms), as well as viruses that are commonly detected in swine operations,** as shown in Table 1. These preliminary results indicate the utility of the AnMBR treated permeate (water) for high quality reuse



(a)



(b)

Figure 3. (a) Lab scale AnMBR COD characteristics and removal efficiency during steady state operation. Average COD removal efficiency of around 80% was achieved with fluctuations corresponding to influent wastewater variations. (b) BOD_5 removal efficiency for the lab scale AnMBR system averaged around 95% during steady state operation, which is superior and leads to effluent quality amenable for reuse.

within the animal operations, provided the concentrations of pharmaceuticals and other contaminants of emerging concern are at acceptable levels.

Beneficial recovery of ammonia-N and Phosphorus-P from the membrane permeate for high value commodity products

Significant research has focused on struvite, vivianite, and apatite recovery from anaerobic centrates with limited to no studies on their bioavailability in soil or ultimate end-use as commodity products.[28,29] Clinoptilolite is a naturally occurring zeolite capable of selectively removing ammonium ions from water via an ion-exchange mechanism.[30] The relative abundance of clinoptilolite in the U.S., its inexpensive cost, and environmentally friendly nature makes it an ideal nitrogen-removal technology.

Removing ammonia using clinoptilolite in a separate ion-exchange (IX) column process has generated interest due to its ability to handle various ammonia loadings and shocks, and its resilience to

Pathogen of concern	Raw swine wastewater	AnMBR treated permeate
Total coliforms (CFU/100 mL)	(350 ± 5.1) x 10^4	(5.2 ± 1.4) x 10^4
Fecal coliforms (CFU/100 mL)	43000 ± 3500	300 ± 90
Porcine Coriovirus 3 (PCV3)	Positive	Negative
Porcine Rotavirus Group C	Suspect	Negative
C. perfringens alpha toxin	Suspect	Negative

Table 1. Summary of key bacterial and viral pathogens of concern detected in the raw swine lagoon wastewater influent and the AnMBR treated swine permeate. The bacteria and viruses were measured using the Colilert and a Tetra core multiplex Realtime PCR unit, respectively.

temperature variations.[31] Additionally, spent clinoptilolite can be regenerated or used as a fertilizer.[32,33] Long-term operation of the clinoptilolite IX process led to >99.5% removal of ammonia-N from the permeate of a pilot-scale, gas-sparged anaerobic membrane bioreactor (AnMBR) treating municipal wastewater (Figure 4A).[34]

The use of iron to precipitate and potentially recover phosphorus is an attractive solution because it simultaneously removes sulfide, which can be hazardous, corrosive, and odorous. Long-term pilot scale operations with municipal wastewater have yielded >85% P capture efficiency from the treated wastewater. Additionally, the recovered sludge contains phosphorus and sulfide or elemental S, in forms amenable to plant uptake.[13,15] Recent efforts in the author's group involve the addition of lime as a coagulant to produce Recovered Nutrient Products (RNPs) that are primarily Calcium Phosphate solids, whose release rates and plant availability can be tunable, an immense advantage to the product, making it superior than conventional fertilizers for food cultivation and other applications (Figure 4B).[35]

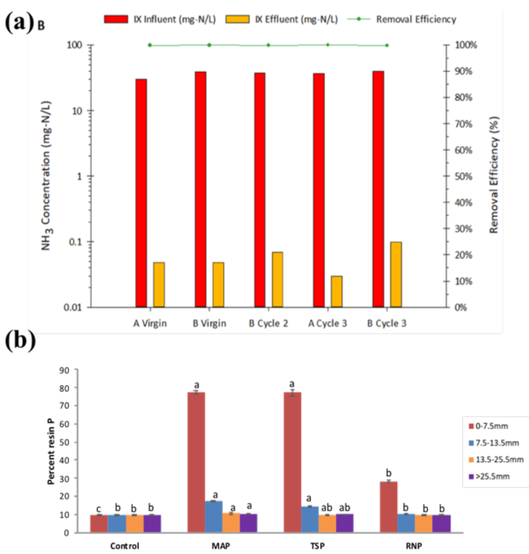


Figure 4. (a) Successive reuse of spent clinoptilolite did not diminish its ammonia sequestration capacity. (b) Resin extractable P (plant available P) indicates promising plant available for the AnMBR derived Phosphorus product.

The author's research has established the lowered energy requirement for the AnMBR platform when it primarily produces methane as shown in Figure 5, compared to conventional activated sludge. Further process optimization will focus on decreasing fouling energy requirements even further by periodic pulse sparging at high flow rates rather than continuous sparging; bioreactor mixing profile modifications in the primary bioreactor.

Broader Significance of the Research

Successful long-term operation of the AnMBR at the bench and pilot demonstrates a viable circular bioeconomy platform for revolutionizing animal operations, especially the swine and dairy sectors, with significant beneficial impacts on the arid/semi-arid region, producing indirect potable water supply and protecting sensitive watersheds from the runoff of the algal bloom triggers – N and P – that will now be sequestered. The research also generates tailored nutrient products for agriculture, namely ammonia-N and Phosphate fertilizers, which can be blended in farmlands at pre-requisite ratios, supporting local crops for supplying the animal operations while supporting a wide variety of crops and vegetables. The generated products will range from organic acids for use as food preservatives, bioplastic manufacturing; ammonia-N as feedstock to fertilizer industry or direct farm use as slow-release fertilizer, or transported for commodity use in renewable energy capture, cosmetics manufacturing; tailored Phosphorus fertilizers for the appropriate soil type, and stabilized biosolids for sustainable land application. Decarbonization of a conventional waste disposal platform integrated with animal operations will be demonstrated through the cross-dis-

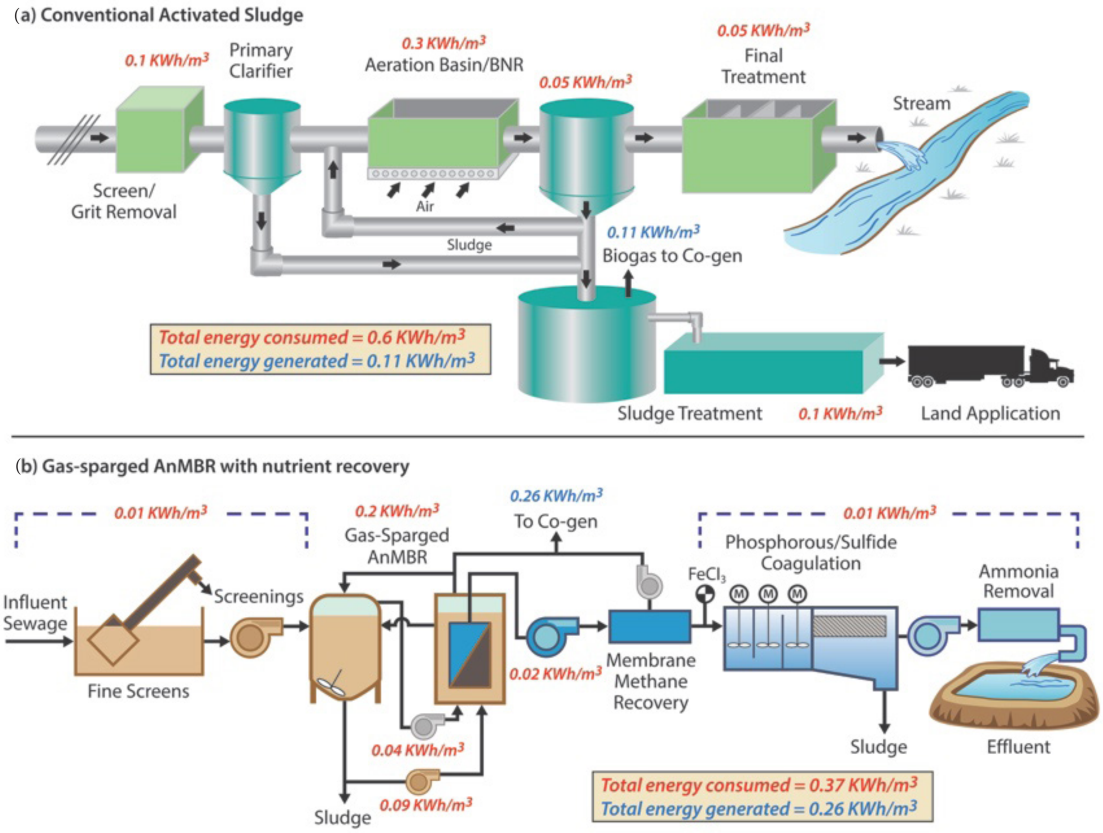


Figure 5. Net energy requirement comparison for (a) conventional activated sludge; (b) AnMBR platform for methane & nutrient capture

ciplinary research proposed, which will inspire other parallel technology platforms at the food-energy-water nexus to replicate these approaches.

The project will spawn new innovations within all public utilities in the rural areas to consider AnMBRs as a means to achieve energy positive operation, while still meeting stringent nutrient discharge goals. Finally, AnMBRs will create a greener workforce in the rural American communities, pivoted around nutrient product marketing, water and renewable energy (biogas) management, as well as reused water reallocation budgeting, without compromising the cropland and food safety.

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