Aquatic Crop Production as a Nutrient-to-Feed Solution for California Dairies

California Livestock Methane Measurement, Mitigation and Thriving Environments Research Program (CLIM3ATE-RP)

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FYTO, INC

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About the CLIM3ATE Research Program

The California Livestock Methane Measurement, Mitigation, and Thriving Environments Research Program (CLIM3ATE-RP) is a research funding initiative administered by the California Department of Food and Agriculture's Office of Agricultural Resilience and Sustainability (OARS).

CLIM3ATE-RP was launched with funds from the Budget Act of 2021 (SB 170, Chapter 240) to support applied research that advances California's climate goals and strengthens the long-term environmental and economic sustainability of the state's livestock sector.

Research Program Focus Areas

CLIM3ATE-RP funded research in three critical areas related to methane emissions and manure management in livestock operations. The three impact areas of the CLIM3ATE Program are:

1. Verification of Methane Reduction Strategies,
2. Alternative Methane Reduction Strategies and
3. Manure Recycling and Innovative Product Development.

In the 2022 funding cycle, CDFA awarded six research projects totaling $4.7 million in funding.

How FYTO's Project "Aquatic Crop Production as a Nutrient-to-Feed Solution for California Dairies" Accomplishes CLIM3ATE-RP Goals

This project was awarded $2,000,000 in funding to support goal 3 of the CLIM3ATE-RP for manure recycling and innovative product development.

FYTO, an agriculture technology company headquartered in Petaluma, CA, proposed a manure recycling and product development project for Impact Area 3 to scale up and bring to market a solution to address nutrient management and feed challenges in California. Through CLIM3ATE-RP, FYTO's aquatic crop farming technology could reduce reactive nitrogen, greenhouse gas emissions, air pollution, and improve water quality, all while producing valuable agricultural ingredients for feed and fertilizer applications. FYTO's project could catalyze a transformational shift in how California manages surplus nutrients and the import of agricultural inputs.

FYTO installed a commercial-scale, automated aquatic crop farm at Rancho Teresita in Tulare, CA. The aquatic cropping system demonstrated value as a nutrient management technology that
efficiently recycles manure effluents into valuable agricultural inputs. The installation allowed for the testing of several key variables (digestate concentration, harvesting frequency, pH adjustment, seasonal yield variations, etc.) at field scale and under real-world conditions. This helped to determine how best to utilize anaerobic digester digestate as the sole source of nutrients for the aquatic plant production. FYTO and dairy industry partners were able to jointly validate the environmental impact and product efficacy of lemna grown on dairy farm lagoon digestate.

The project had six main objectives. These objectives were:

1. Commercial Dairy Operability to demonstrate that lemna can be reliably grown, processed, and used at a commercial scale on a California dairy operation.
2. Lemna Yield & Composition to measure, analyze, and independently validate the yield and composition of Lemna grown on dairy manure effluent.
3. Product Safety & Efficacy to measure, analyze, and independently validate the safety and efficacy of lemna grown on dairy manure effluent for use as high-protein dairy feed.
4. Environmental Impact to measure, analyze, and independently validate the air quality, water quality, and use-efficiency, nutrient management, and overall life cycle impact of farming lemna on a California dairy operation.
5. Economic Feasibility to conduct and independently validate a techno-economic analysis and economic benefits assessment of on-dairy lemna farming at different scales and locations in California.
6. Producer Engagement to develop and implement a producer outreach program that fosters bilateral discussion about aquatic crop farming with California dairies through farm-centric events and services.

This final report evaluates each objective and its findings.

Objective 1: Commercial Dairy Operability

Key Activities and Take-Aways:

1. After conducting successful on-dairy test plots, Fyto scaled operations to a total of 3.3 acres and harvested over 1 million lbs. of fresh duckweed that were grown entirely on commercial dairy digestate.
2. Successfully demonstrated operability of lemna production at commercial scale for over 12 months.
3. Built and validated 2 autonomous Gen3 robotic harvesters in 2024 and designed and partially constructed a larger, cost-optimized Gen4 system in 2025.

Summary:

Fyto successfully demonstrated the operability of its aquatic crop system at a commercial dairy in Tulare, CA. Fyto tapped into the dairy's existing digestate pipeline and well water to grow its aquatic crop on a plot that had previously been used for wheat and corn production. During the 2024 season, the company expanded its grow operations to 3.3 total acres at Rancho Teresita. More than one million pounds of fresh lemna (duckweed) were harvested between 2024 and mid-2025.

Lessons from initial system design and operation were used to improve system efficiency and reduce costs. These insights directly informed the development of Fyto's fourth generation (Gen4) growing and harvesting system, featuring a simplified, cost-optimized design and two self-driving harvesters. These upgrades enabled more consistent performance and significantly reduced operating expenses, advancing Fyto's vision for scalable, low-input aquatic crop production.

Permit acquisition and farm construction were completed ahead of the 2024 growing season. Full commissioning and validation occurred in mid-2024, enabling robust yield testing and data collection.

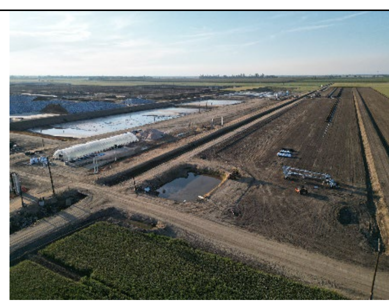
		
Smaller volume "test plots" were employed to derisk operating parameters	A former cornfield adjacent to the digester was transformed into a Fytofarm in early 2024	The farm was operated for approximately 13 months before being decommissioned

Figure 1: Test plots, early construction, and multi-acre operation of aquatic cropping system at Rancho Teresita

While over 1 million pounds of fresh lemna were grown and harvested from the operation, it was unable to be fed to the cows on the operation based on the CDFA Commercial Feed Regulatory Program's opinion that it was not a homegrown feed that would be exempt from a commercial permit. The Fyto team dried as much as possible, but the majority of the crop needed to be landfilled which was a very unfortunate outcome that frustrated Fyto, the host dairy, and many stakeholders that were looking to see the material used on-farm. Despite the challenges with on-farm feeding, Fyto identified parties in other States that needed access to R&D material for controlled feeding in grant-funded research.

The project was a marked progression in the state of the art on aquatic crop production and circular wastewater valorization. In addition to running the system for over 13 months, Fyto's engineering and operations teams were able to make large improvements in the projected capital and production costs of lemna farming. As shown in Figure 2, Fyto was able to implement 2 different generations of automated harvesting machines on the project site.

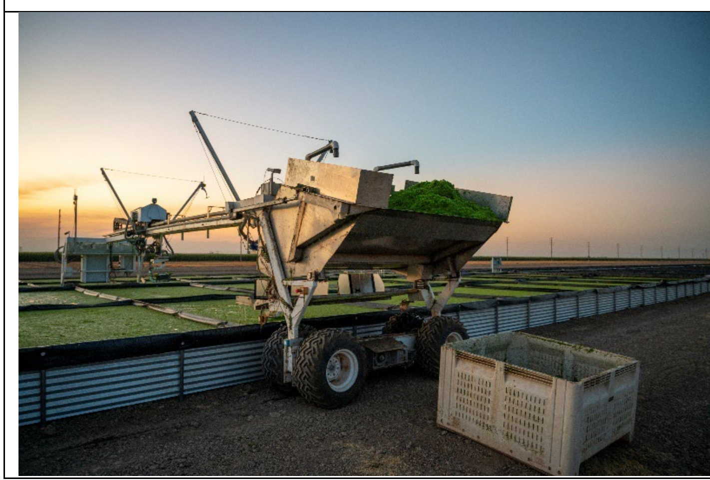
Fyto's 3rd Generation Harvesting Machines Used to Operate the Fytofarm of this project	The prototype of Fyto's 4th Generation Harvesting Machine that could serve 4X the area for similar capital costs as the 3rd generation machine
	

Figure 2: Fyto's 3rd generation and 4th generation machines were operated on the project site at Rancho Teresita

Objective 2: Establish Lemna Yield and Composition

Key Activities and Take-Aways

1. Yield tracking showed a potential seasonal productivity of ~12 g/m²/day, or ~15 dry tons/acre/year when the best practices conditions were employed (i.e. digestate introduction rate, harvesting frequency).
2. Over 12 months of nutritional composition data showed consistently high protein (~36% DW) and digestibility.
3. Daily system monitoring and phenotyping informed optimal cultivation practices.

Summary:

Fyto successfully established and validated lemna yield and composition at commercial scale. The company weighed every harvest, tracked wet and dry matter yields daily, and consistently measured solids content using moisture analyzers. One of the main objectives of the project was to establish potential yields as a function of several variables, measured in real-world farming conditions over a sufficient period of time at a sufficiently large scale. It was important not just to track biomass yield, but the composition of the crop to track important parameters such as protein yield and starch yield.

Twelve months of composition data were collected and analyzed across several metrics including crude protein, fiber, fat, ash, and digestibility. On average, lemna samples showed 35.7% crude protein on a dry weight basis, with total digestible nutrients (TDN) averaging 75.8% DW. Variability was perceived to be within the accepted standards of other feed ingredients, indicating stable nutrient composition under field conditions.

Table 1: Detailed forage analysis for lemna grown on dairy digestate at Rancho Teresita

Forage Analysis				
Analyte	**Unit**	**Average**	**Standard Deviation**	**Sample Count**
Dry matter AR	%	93.78	1.66	30
Protein (crude) AR	%	34.16	1.69	41
Protein (crude) DW	%	35.68	1.51	26
Fat (crude) AR	%	2.4	0.61	38
Fat (crude) DW	%	2.36	0.65	23
Fiber (crude) AR	%	8.69	1.5	38

Fiber (crude) DW	%	9.5	1.73	23
Fiber (acid detergent) AR	%	16.8	3.05	15
Fiber (acid detergent) DW	%	17.95	3.31	15
Fiber (neutral detergent) AR	%	20.81	3.7	10
Fiber (neutral detergent) DW	%	22.26	3.88	10
Ash AR	%	20.5	2.18	38
Ash DW	%	22.43	2.69	23
Nitrate (NO3) AR	%	0.19	0.12	12
Total digestible nutrients AR	%	70.74	2.06	10
Total digestible nutrients DW	%	75.76	2.18	10
Net energy (lactation) AR	Mcal/lbs	0.74	0.02	10
Net energy (lactation) DW	Mcal/lbs	0.79	0.03	10
Net energy (maint.) AR	Mcal/lbs	0.73	0.02	10
Net energy (maint.) DW	Mcal/lbs	0.78	0.03	10
Net energy (gain) AR	Mcal/lbs	0.49	0.02	10
Net energy (gain) DW	Mcal/lbs	0.52	0.02	10
Lignin AR	%	3.75	3.76	6
Lignin DW	%	4.02	4.01	6
Loss on ignition (OM) AR	%	70.83	3.51	10
Loss on ignition (OM) DW	%	75.83	3.21	10
Water insoluble nitrogen (WIN) AR	%	4.03	0.04	2
Water soluble nitrogen AR	%	1.6	0.18	10

All values are As-Received (AR), unless noted as Dry Weight (DW). n.d. = not detected. For averaging calculations, n.d. = 0.

Regarding yield optimization, Fyto's team was able to determine an optimal protocol of pH range, harvesting frequency, nutrient concentration, and nutrient addition rate at different times of year for this site under a full year of growing, leading to average production rates of just over 12 g/m²/day dry matter—equivalent to approximately 15 dry tons per acre per 275 day growing season—highlighting lemna's potential as a high-yield protein crop. Given the large swings in monthly temperatures and solar flux in the Central Valley (for instance in February vs July), the range of productivity was quite high (from under 3 g/m²/day dry matter in the winter months to over 20 g/m²/day in the summer. So, while the overall annual protein yield is substantially higher than land-based protein crops like soy, the ramp up and ramp down of the monthly yields need to be incorporated into planning for uses of the lemna crop as well as nutrient recycling benefits of the Fyto system. There are more optimal environmental conditions as well as digestate compositions that could drive the yields up further and smooth out the seasonal variability, but this was not a focus of the current project.

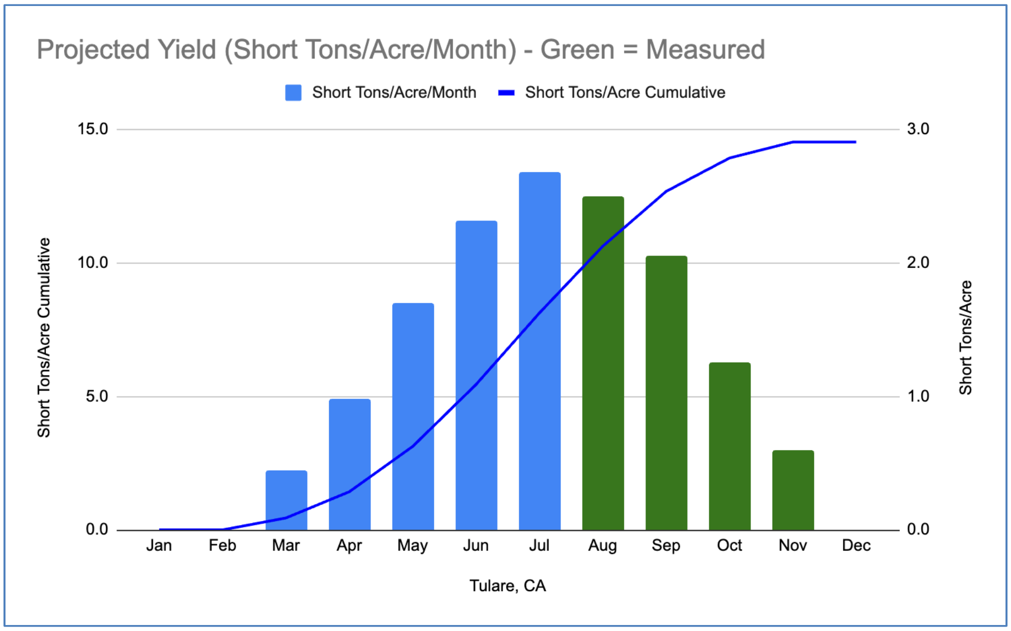


Figure 3: Cumulative yield model with actual yields for Aug-Nov 2024 (farm was not fully operational before then)

Since 2024 was only a partial season due to ramp up of the system, it is helpful to include 2025 data to determine what complete annual season yields might be. Figure 4 stitches together 2024 and 2025 actual yield data overlayed on a modeled monthly yield that would sum to 15 tons dry matter per acre per year. The shape of this modeled curve is based on grow degree days. As can be seen in Figure 2, the system was tracking toward a similar yield to the modeled outcome.

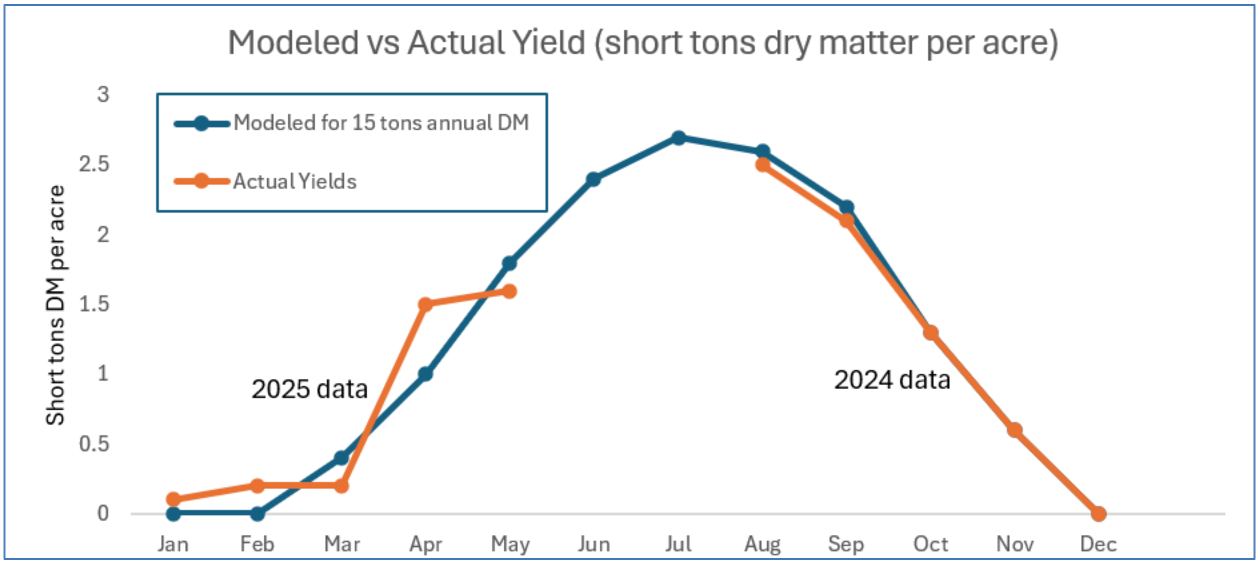


Figure 4: 2024 and 2025 actual yields overlayed on modeled 15-ton DM annual yield

When combining the yield measurements with the composition measurements, it is determined that the installed Fyto operation could surpass 10,500 pounds of protein per acre per year. Compared to the leading protein crops relevant to dairy (alfalfa, soy, canola), Fyto could produce several times as much protein per acre, all while addressing nutrient management challenges on the dairy.

Table 2: Estimated protein yields from leading land crops vs Fyto lemna

Crop	**Region**	**Annual Yield**	**Crude Protein %**	**Estimated Protein Yield (lbs/acre/year)**	**References**
Alfalfa	California	7–9 tons dry matter/acre/year	17–22%	2,380–3,960 lbs	https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Alfalfa_Production_CA.pdf
Soybeans	Midwest (e.g., Iowa)	1.1-1.2 tons of dry matter per yr	~40%	980–1,072 lbs	https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=US&crop=Soybean
Canola	Canada (e.g. Sask.)	0.7-0.96 tons of canola per acre, 55-60% seed à meal	Meal = ~36%	279–456 lbs (from canola meal)	https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=CA&crop=Rapeseed
Fyto Lemna	California	14–20 tons dry matter/acre/year	35–40%	**9,800–16,000 lbs**	Internal data (Fyto Inc., est. based on cultivation results)

Phenotyping

Routine phenotyping was routinely performed on lemna minor and lemna gibba, the two primary strains used in Fyto's system. Observations showed seasonal performance variation between strains, with gibba showing improved growth in hotter months and minor being more prevalent in cooler months. This dual cropping strategy proved important as tests with monocropping did not fare as well over the season. Daily monitoring of pH (target range 6.5–7.0), electrical conductivity (<5000 µS/cm), and temperature informed best practices for nutrient and algae management.

These data were compiled into a comprehensive yield and composition report, supporting the viability of lemna as a consistent, high-protein, and digestible feed ingredient grown entirely on recycled dairy waste.

Objective 3: Evaluate Product Safety and Efficacy

Key Activities and Take-Aways

1. Extensive quality testing tracked heavy metals and biological pathogens.
2. Fyto's lemna was tested in controlled feed trials for both sheep and broiler chickens by Penn State. The results demonstrated positive outcomes in health, growth, and feed efficiency for Fyto-fed animals
3. Additional large-scale animal (dairy cow) trials are underway at Penn State with peer-reviewed publications pending.

Summary:

Material Safety
As the objective of Fyto's technology platform is to safely and effectively transform nutrient management challenges into feed and fertilizer solutions, it was important to track potential contaminants, including heavy metals and biological pathogens.

Heavy Metals
In 2024, 10 separate heavy metal assays were conducted, and all values were found to be within safe limits for comparable feed ingredients and in many cases, were below detection limits.

Table 3: Heavy metals concentrations from lemna grown on digestate at Rancho Teresita

Arsenic (Total) (mg/kg)	**Zinc (Total) (mg/kg)**	**Boron (Total) (mg/kg)**	**Iron (Total) (mg/kg)**	**Cobalt (Total) (mg/kg)**
<1.00	238	488	1390	0.85
n.d.	242.3	410	1190	n.d.
< 5.0	170.2	337	1102	< 1.00
< 5.0	119.9	360	1106	< 1.00
< 5.0	99.8	349	1815	1.06
< 5.0	80.6	349	2202	< 1.00
< 5.0	97.8	349	1501	< 1.00
< 5.0	99.8	317	1654	1.34
< 5.0	83.5	331	1935	1.46
< 5.0	81.5	335	3189	1.90
Molybdenum (Total) (mg/kg)	**Selenium (Total) (ppm)**	**Manganese (Total) (mg/kg)**	**Cadmium (Total) (mg/kg)**	
2.2	0.35	153	0.05	
2.0	n.d.	153	n.d.	

2.0	< 5.0	142	< 0.50	
1.7	< 5.0	176	< 0.50	
1.1	< 5.0	162	< 0.50	
1.9	< 5.0	169	< 0.50	
< 1.0	< 5.0	158	< 0.50	
< 1.0	< 5.0	238	< 0.50	
< 1.0	< 5.0	278	< 0.50	
< 1.0	< 5.0	318	< 0.50	
Copper (Total) (mg/kg)	**Mercury (Total) (mg/kg)**	**Nickel (Total) (mg/kg)**	**Lead (Total) (ppm)**	
6.0	0.02	2.0	0.27	
5.7	n.d.	2.0	n.d.	
5.6	< 0.05	2.0	< 5.0	
5.2	< 0.05	2.3	< 5.0	
5.8	< 0.05	2.5	< 5.0	
6.2	< 0.05	4.7	< 5.0	
5.2	< 0.05	2.6	< 5.0	
5.9	< 0.05	2.8	< 5.0	
5.7	< 0.05	3.2	< 5.0	
7.0	< 0.05	5.3	< 5.0	

Pesticides and Mycotoxins
On 5 separate occasions, material was inspected for a wide variety of mycotoxins and pesticides through third-party laboratory testing. In all 5 cases, the material received a pass for these categories of potential toxins.

Self-affirmed GRAS Panel Consensus Opinion
In 2024, an independent panel of three subject-matter experts was assembled to assess the safety of Fyto's lemna as an ingredient for all animals. The dossier that the expert panel reviewed included dozens of laboratory tests as well as hundreds of journal article references compiled by Fyto's regulatory team. This was in support of Fyto's AAFCO ingredient definition application and subsequent FDA submission (once AAFCO/FDA MOU was terminated). The expert panel found that Fyto's ingredient was indeed safe for all animals if provided in accordance with good animal nutrition practices. This consensus statement follows:

CONCLUSIONS

We, the members of the Expert Panel, have independently and collectively critically evaluated the information summarized above and conclude that dried water lentils manufactured by Fyto in accordance with cGMP and meeting appropriate feed-grade specifications, is safe and suitable for use as a source of protein in the feed of all animal species.

We further conclude that the intended use of dried water lentils as a source of protein in feed for all animal species in the U.S. is Generally Recognized as Safe (GRAS) based on scientific procedures.

It is our opinion that other qualified experts would concur with these conclusions.

Signer ID: CPRMECBKAG...
David Bechtel, Ph.D.
Bechtel Consulting, Inc.

10/24/2024 PDT
Date

Signer ID: REFTYHLPZO...
James Drackley, Ph.D.
University of Illinois Urbana-Champaign

10/25/2024 PDT
Date

Signer ID: ASZOLO4NUP...
Martin Nyachoti, Ph.D.
University of Manitoba

10/24/2024 PDT
Date

Figure 5: Consensus statement from expert panel on the safety of Fyto's lemna

Additional Animal Feeding Trials for Safety and Efficacy

Professors Rachel Brannen and Alexander Hristov of Pennsylvania State University have independently been conducting research on the potential for lemna to serve as a circular nutrient recycler and feed ingredient. They were awarded a federal grant to study the safety and efficacy of manure-grown lemna on several animal species, but lacked sufficient quantities of lemna for testing. Through this project, Fyto was in a unique position to help Penn State conduct its research while also learning from these important studies. In May 2024, Fyto shipped 750 pounds of dried and milled lemna to PSU for use in controlled studies on ruminants and poultry.

The first trial evaluated lemna in the diets of nine ewes. The second trial tested its use in broiler chickens with a sample size of 480 birds. Both studies measured key metrics such as feed intake, body weight, feed conversion ratio, live weight gain, and mortality. Across both animal types, lemna inclusion showed positive effects and did not raise any safety concerns. These results are now being prepared for submission to peer-reviewed journals and are not yet available to share here.

In July 2025, Fyto shipped an additional 15,000 pounds of dried, pelleted lemna to Penn State for a comprehensive dairy cow feeding trial. These studies are expected to yield deeper insights into the performance of lemna in commercial feeding systems, with further publications anticipated by the end of 2025.

Objective 4: Evaluate Environmental Impact

Key Activities and Take-Aways

1. Preliminary analysis indicates lemna production may reduce GHG emissions by 2-3 tCO_2e per dry ton of lemna when displacing conventional protein feed such as canola meal, depending on assumptions. Given yield estimates, this amounts to potentially 30-45 tCO_2e mitigated annually per acre of Fytofarm.
2. Air emissions study carried out by CE Schmidt showed reduced methane, ammonia, CO2 and VOCs compared to wastewater lagoons and flood-irrigated corn.
3. Lemna significantly improves nutrient utilization/reduces nutrient loss and has potential to reduce lagoon size and associated emissions when built at multi-acre scale.
4. Fyto's water use was found to be within norms for reference values (open ponds and irrigated crops) and was found to be substantially lower when protein yield per gallon of water was taken into account.

Summary:
Fyto conducted a multifaceted assessment of the environmental impact of lemna cultivation using dairy manure effluent. A preliminary screening-level life cycle assessment (LCA), performed by an external consulting firm, estimated that substituting lemna for imported feed ingredients like canola meal in Central Valley dairy diets could reduce greenhouse gas (GHG) emissions by approximately 1.35 metric tons of CO_2-equivalent per dry ton of lemna. A hotspot analysis conducted by the firm helped highlight areas where Fyto could further reduce its greenhouse gas emissions – these areas were primarily sulfuric acid addition, and materials of construction for the growing environment pond liner. When incorporating process improvements and system upgrades implemented during the 2024 season, projected reductions increased to 1.98 tCO_2e per dry ton compared to the conventional canola diet. This is a 78.8% reduction in greenhouse gas emissions compared to the reference case.

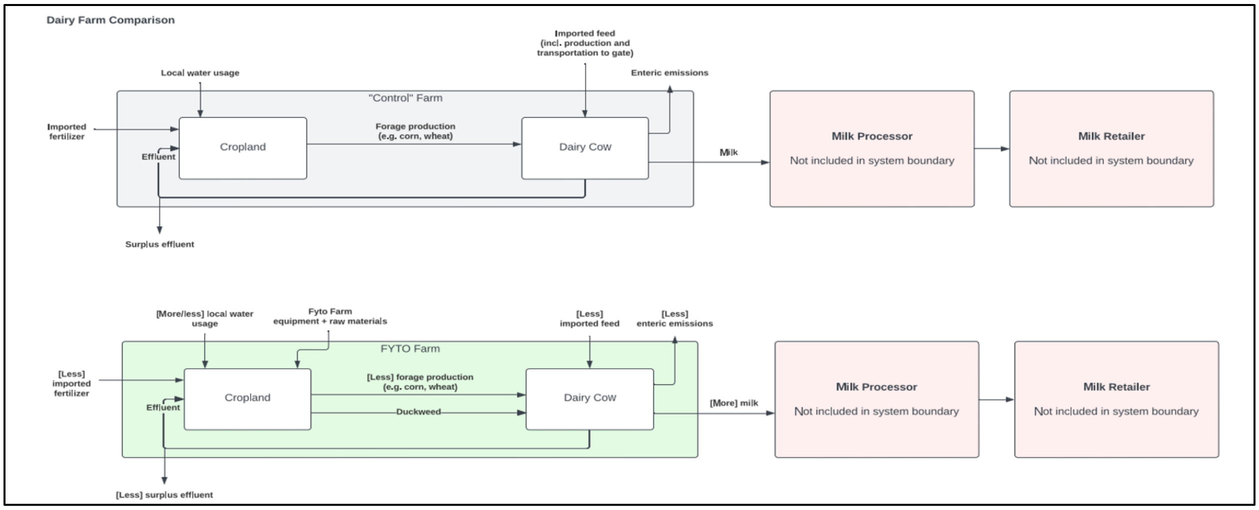


Figure 6: Baseline vs Fyto cases used for 3rd party LCA. Although enteric emissions and increased milk production were possible as written, they were not included in the analysis until further data could be produced.

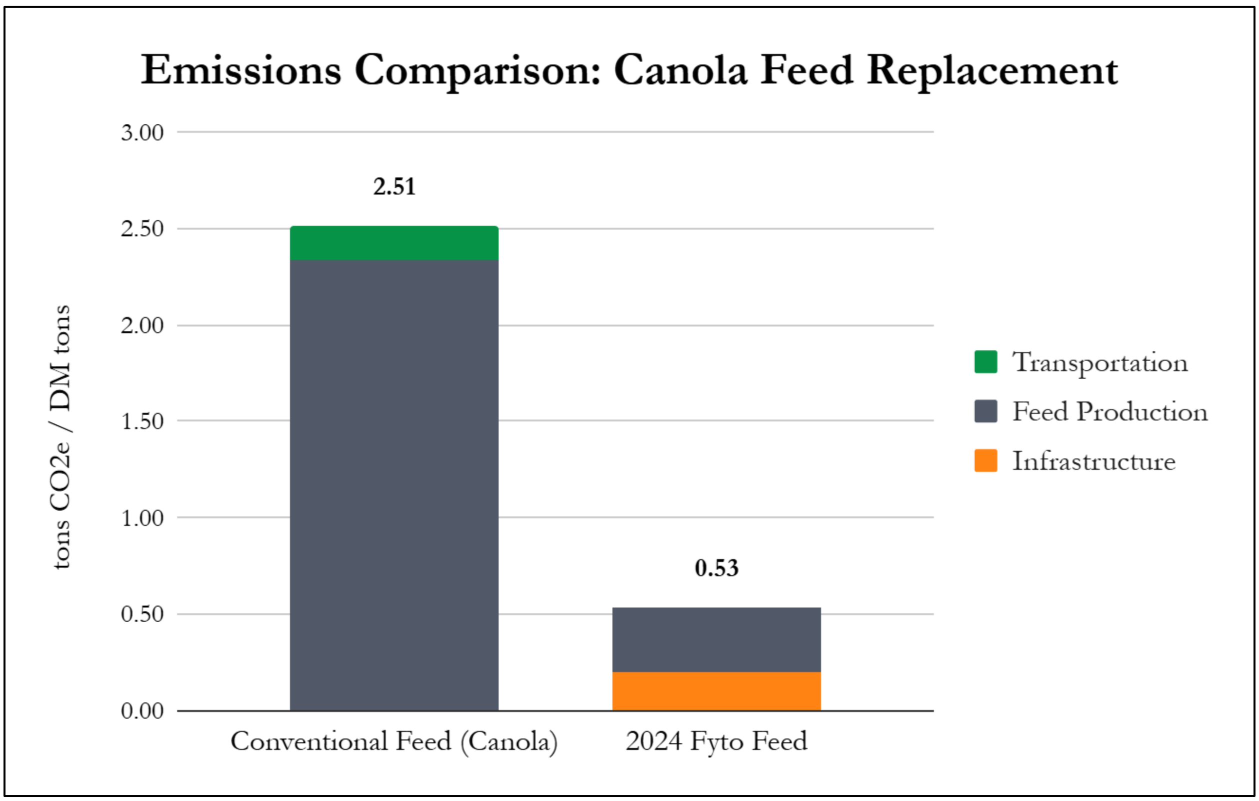


Figure 7: 3rd Party Screening LCA demonstrated nearly 80% reduction from baseline emissions with Fyto largely based on the emissions benefits of lemna production vs canola production.

Prior third-party cow feeding trials utilizing the GreenFeed enteric methane measurement system demonstrated a potential reduction of enteric methane of more than 7% on Fyto-fed cows vs canola-fed cows. This would translate to an additional 1+ tCO_2e per dry ton of lemna produced.

Direct Emissions Measurements

An independent air emissions field study conducted by CE Schmidt found that lemna cultivation resulted in significantly lower greenhouse gas emissions when compared to both wastewater lagoons and flood-irrigated corn fields. These findings underscore the potential for aquatic crop systems to reduce dairy-related emissions not only through feed replacement but also by improving nutrient capture and reducing reliance on traditional waste treatment infrastructure.

		
Flux chamber testing on dairy digestate lagoon	Flux chamber testing on Fyto aquatic cropping system	Flux chamber testing in adjacent silage corn field

Figure 8: Direct gaseous emissions measurements were conducted by CE Schmidt at Rancho Teresita

Table 4: Emissions flux (mg/m2 per min) of various compounds for lagoon vs corn field vs Fytofarm at 2 different NH4+ concentrations (15ppm vs 60ppm)

	Compound and CAS										
	TNMNEO (VOC)	**Ammonia**	**Methane**	**Carbon Dioxde**	**Nitrous oxide**	**Acetaldehyde**	**Ethanol**	**Acetone**	**Methanol**	**Carbon disulfide**	**2-Butanone (MEK)**
Source		**7664-41-7**	**74-82-8**	**124-38-9**	**10024-97-2**	**75-07-0**	**64-17-5**	**67-64-1**	**67-56-1**	**75-15-0**	**78-93-3**
FYTO											
Typical Loading (316) AM	0.0345	0.0017	0.0402	4.77	0.0187	0.0084	0.0044	0.0012	0.0000	0.0000	0.0000
Typical Loading (316) PM	0.0875	0.0029	0.0452	5.23	0.0215	0.0043	0.0000	0.0060	0.0029	0.0029	0.0015
Avg	0.0610	0.0023	0.0427	5.00	0.0201	0.0063	0.0022	0.0036	0.0014	0.0015	0.0007
High Loading (326) AM	0.0380	0.0019	0.0414	8.60	0.0254	0.0122	0.0058	0.0025	0.0000	0.0000	0.0016
High Loading (326) PM	0.0429	0.0024	0.0440	7.99	0.0287	0.0072	0.0040	0.0018	0.0021	0.0000	0.0001
Avg	0.0405	0.0022	0.0427	8.29	0.0270	0.0097	0.0049	0.0021	0.0011	0.0000	0.0008
FYTO Overall Average	0.0508	0.0022	0.0427	6.65	0.0236	0.0080	0.0036	0.0029	0.0013	0.00075	0.00079
Lagoon	0.0877	0.0361	14.7	50.85	0.0174	0.0064	0.0069	0.0016	0.0015	0.00075	0.00028
Corn Field	0.0871	0.0060	0.0421	19.19	0.0539	0.0055	0.0011	0.0017	ND	ND	0.00009

Digestate Use

Digestate served as the sole source of nutrients for Fyto's operation at Rancho Teresita. Given the high productivity and protein content of Fyto's lemna, nitrogen is generally the rate-limiting nutrient in digestate. Given that every dairy operation is slightly different, digestate composition from farm to farm differs. Fyto obtained initial estimates of digestate usage from the test plot that was run in 2023 (shown in Figure 1). Fyto took advantage of the opportunity presented by this large-scale research platform to test low N loading and high N loading to measure any differences in yield, plant composition, emissions from the growing environment, etc. The low N loading condition aims to keep the growing environment at an NH4+ concentration of 15ppm while the high loading N environment aims to keep the growing environment at 60ppm NH4+. One immediate benefit of the higher loading rate is that less dilution is required. The digestate sampled at Rancho Teresita had an average NH4+ concentration of 338 ppm NH4+ as shown in Table 5, which implies that the low loading rate requires a 22.5X dilution while the high loading rate requires substantially lower 5.6X dilution. Prior R&D and evidence in the literature indicate that considerably higher loading rates are possible (Fyto successfully tested 120ppm NH4+, for instance), but the 15ppm and 60ppm NH4+ values were selected based on the test plot work at Rancho Teresita specifically.

Table 5: Average digestate composition from series of grab samples throughout 2024 season

Digestate Composition			
Analyte	**Unit**	**Average**	**Standard Deviation**
pH	--	7.28	0.25
Conductivity	mS/cm	5.65	1.07
Ammoniacal Nitrogen	mg/L	338.3	70.9
Total Kjeldahl nitrogen (TKN)	mg/L	397.7	77
Nitrite nitrogen	mg/L	0.077	0.025
Organic nitrogen	mg/L	43	37.3
Beryllium (total)	mg/L	0.00063	0.00071
Boron (total)	mg/L	0.98	0.03
Fluoride	mg/L	n.d.	--
Sodium (total)	mg/L	272.7	11
Magnesium (total)	mg/L	100.7	20.2
Phosphorus (total)	mg/L	70.5	17
Sulfur (total)	mg/L	28.3	10.4
Potassium (total)	mg/L	486.7	43.4
Calcium (total)	mg/L	134.7	29.7
Chromium (total)	mg/L	n.d.	--
Manganese (total)	mg/L	0.5	0.22
Iron (total)	mg/L	0.91	0.19
Nickel (total)	mg/L	0.027	0.031
Copper (total)	mg/L	0.027	0.012
Zinc (total)	mg/L	0.21	0.05
Arsenic (total)	mg/L	0.0038	0.0004
Selenium (total)	mg/L	0.0013	0.0023
Cadmium (total)	mg/L	0.0013	0.0023
Antimony (total)	mg/L	n.d.	--
Barium (total)	mg/L	0.09	0.028
Mercury (total)	mg/L	n.d.	--
Thallium (total)	mg/L	n.d.	--
Lead (total)	mg/L	n.d.	--

n.d. = not detected. For averaging calculations, n.d. = 0.

In October 2024, a steady state test was conducted to determine if the loading rates had any effect on the plant composition. The results of this test are shown in Table 6. As can be seen, the higher NH4+ concentration in the growing environment evidently led to an increase in the protein levels of approximately 13%. The total dry matter lemna yields from these two sections were statistically similar although separate experiments conducted in smaller tanks indicated that the 60ppm NH4+ concentrations could lead to higher protein and higher dry matter yields. More work would need to be conducted at scale to observe whether these effects were statistically significant over a sufficient period of time. Fyto's team felt it was important to understand the emissions implications and overall nitrogen balance of lemna growing at these two different levels and conducted side by side comparisons. As shown in Table 4, emissions from the low vs high NH4+ zones weren't vastly different although it is worth noting that nitrous oxide emissions were slightly higher in the higher loading section than the typical/lower loading section.

Table 6: Crude protein average in low vs high NH4+ sections

Low vs High NH4 Sections - Crude Protein Comparison *October 2024*		
Parameter	**Section 328 (15ppm NH4+)**	**Section 329 (60ppm NH4+)**
Crude Protein Average *(+/- StDev)*	37.7% *(+/- 1.3)*	42.6% *(+/- 0.4)*
Estimated Nitrogen Production (lbs N / acre / yr)	1576	1695

Nitrogen Balance:

Since nitrogen is the rate-limiting nutrient for lemna and it is also one of the nutrients under high regulatory scrutiny, a nitrogen mass balance was carried out to best understand the efficiency of nitrogen capture from Fyto lemna. This was conducted on a growth section (Section 328) that was run at the low/typical NH4+ concentration of 15ppm as well as another section (Section 329) the high concentration of 60ppm. Fyto measured the digestate and makeup water nitrogen as well as the initial N contained in the growth media. Fyto also directly measured the plant material harvested and average nitrogen value as well as the nitrogen gaseous emissions as previously described from Table 4. It was not feasible for Fyto to directly measure the N solids accumulation or the N being put into plant inventory on the growth environments, but those were believed to be relatively minor N sinks in this study.

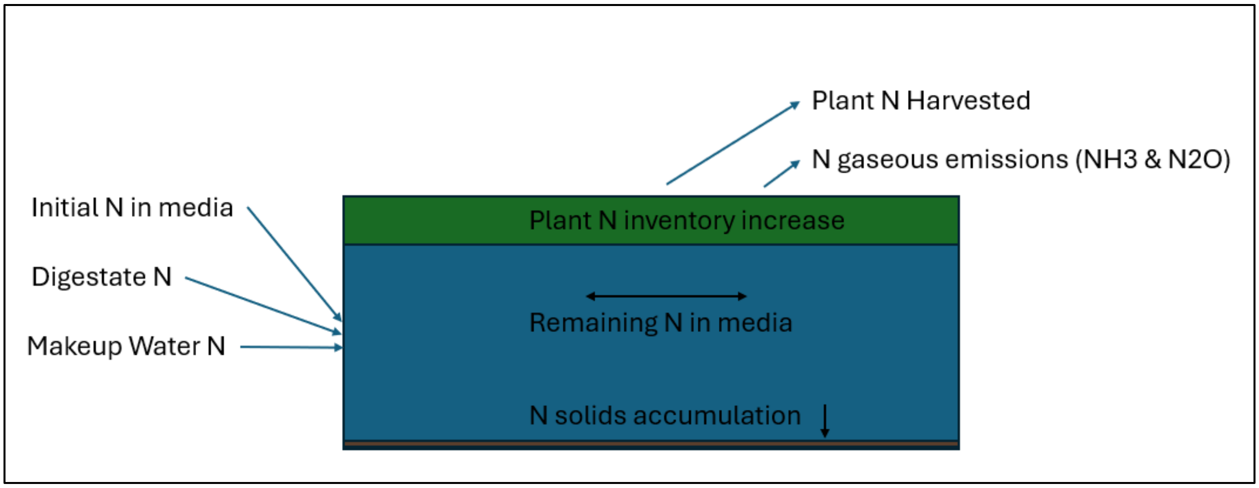


Figure 9: Depiction of nitrogen balance conducted in this project on high and low/typical NH4 loaded sections from 8/22/2024-11/20/2024

The mass balance showed that for the low (15ppm) NH_4^+ concentration condition, 90.2% and 9.8% of the nitrogen came from the digestate and well water, respectively. In the high (60ppm) NH_4^+ concentration condition, 93.7% and 6.3% of the nitrogen came from the digestate and well water, respectively. The makeup water was found to contain both ammonium and nitrate. Based on the remaining measurements, the low concentration growth section was estimated to have a 93% nitrogen use efficiency, while the higher concentration growth section had a 74% nitrogen use efficiency. In both cases, less than 4% of the total nitrogen was estimated to leave as gaseous emissions. The most likely explanation for unaccounted nitrogen is in settled solids in the bottom of the growing environment which were visually evident but impossible to weigh accurately across the large growing environment size without disrupting the system. This nitrogen balance work understates the multiparameter decision that needs to be made regarding NH_4^+ concentration. Higher tends to mean higher yields, higher protein, but potentially higher nitrogen loss and settled solids.

Water Use

Given the concern around water use in California, particularly given Fyto's crops are aquatic, the Fyto team carefully catalogued overall water use and made reasonable estimates as to the amount of water that left the system as evapotranspiration vs the drying of harvested plants. Table 5 includes summarized results of these measurements and calculations. It is important to note that establishing ponds requires 1.5-acre ft, since the farm is operated with approximately 1.5 ft of water to provide sufficient thermal buffering from the wide temperatures experienced diurnally in the San Joaquin Central Valley. This water is not used, per say, as much as it is borrowed. It can be returned to the lagoon at any point included during the cleaning operations that are anticipated once every two years. The second value in Table 7, however, can be regarded as the amount of water that is consumed by the operation per year and is broken into subcomponents of harvested water that is lost to drying and evapotranspiration from the crop as it grows.

Table 7: Water Use/Water Loss from Fytofarm

Source of Water Use/Loss	Per Acre Usage	Comments
Establishing of ponds for startup	1.5 acre-ft	This is the initial fill required before introducing plants
Steady state makeup water	2.85 acre-ft	Steady state makeup water is the amount of well water that needs to be added per season due to ET and harvested water in plants.
Estimated harvested water in plants	0.21 acre-ft	15 tons of dry matter equates to approximately 300 tons fresh harvested material
Estimated ET	2.85-0.21 = 2.64 acre-ft	Amount of water that is lost due to steady state ET per year with lemna at Rancho Teresita

As can be seen, the total water consumed is estimated to be 2.85 acre-ft per acre per year. This is approximately half the water consumed by alfalfa per acre per year in California's Central Valley[1]. Combined with the protein yield information shown in Table 2, Fyto's lemna has the potential to be more than 5X as water efficient (pounds protein per acre ft water) as alfalfa. This is a crucial finding as California faces extremely challenging water resourcing ahead. The fact that Fytofarms can utilize lagoon effluent (not recommended for alfalfa[2]) provides yet another compelling reason why it should be strongly considered as a cropping system for sustainable dairy farming in California and beyond.

[1] https://alfalfa.ucdavis.edu/sites/g/files/dgvnsk12586/files/media/documents/UCAlfalfa8287ProdSystems-reg.pdf

[2] https://www.ars.usda.gov/ARSUserFiles/50901500/px-based_v3.2/educ-matrls/pdfs/FS_manure-apply-perennial-forage.pdf

Objective 5: Evaluate Economic Feasibility

Key Activities and Take-Aways

1. Fyto conducted detailed assessments to establish current and future capital costs and production costs for lemna
2. Regional variability in feed prices, nutrient management pressure, water availability, and carbon pricing affects on-farm economics.
3. Economic viability is strongest when lemna production is paired with GHG or nutrient management revenue or if lemna is exported off-farm as a higher value product.

Summary:

While constructing and operating the multi-acre facility as part of this project, Fyto completed an initial techno-economic assessment to evaluate the commercial viability of lemna farming on California dairies. The economic case for Fyto, like any farming method, requires consideration of capital costs as well as ongoing operating costs required to run the facility. Fyto's team used the learnings from earlier work as well as this project to design and test revisions to the system that would lead to compelling return on investment for those running Fyto facilities.

The ultimate goal of Fyto is to provide an on-farm solution that dairy producers can utilize to simultaneously solve nutrient management and feed challenges on their farm while greatly reducing greenhouse gas emissions. There is a clear path to the unit economics that allows this model to work with an acceptable payback period that aligns with other choices in dairy farm technology. Until those capital cost and operating cost goals are achieved, however, Fyto would recommend financing, building, owning, and operating the Fytofarms on behalf of the dairy producers and maximizing the revenue from lemna production by exporting it off-farm for higher value applications. The dairy still realizes the nutrient management benefits plus rental income for the land being utilized (modeled at $500/acre annually) by Fyto without having to absorb the capital risk and potentially long payback period for these first installations. As capital and operating cost reductions are achieved, it will make sense to evolve the business into selling systems and services directly to the dairy operations.

Current Economics:

When using 2025 capex of $93,400 per acre and COGS of $359 per dry matter ton for fresh lemna on-farm, it is clear to see that the payback period is not attractive without CAPEX offsets or higher revenue streams. This assumes zero monetized value for nutrient management or carbon emissions reduction. Using simple payback period calculations and basic assumptions:

$400 --	**$359**	**= $41**	**X 15 tons/acre**	**=$615/acre per yr**
Current concentrate price	Fyto COGS 2025	Savings per ton with Fyto	Yield of Fyto per acre	Savings per year per acre with Fyto

$93,400 /	**$615**	**= 152 years**
Current CAPEX per acre	Savings per year	Simple payback

Rather than concluding that the projected payback period rendered the concept unviable, the Fyto team prioritized strategies to reduce capital expenditures (CAPEX) and cost of goods sold (COGS), while concurrently identifying near-term opportunities for increased revenue generation to bridge the gap until unit economics could support on-farm conventional feed replacement.

$3000/ton -	**$951/ton**	**= $2049**	**X 15 tons/acre**	**=$30,735/acre per yr**
Lemna specialty ingredient sales price	Fyto COGS 2025 for dried lemna	Earnings per ton	Yield of Fyto per acre	Earnings per acre with Fyto

$93,400 /	**$30,735**	**= 3 years**
Current CAPEX	Fyto COGS 2025	Simple payback

Clearly, this approach presents much more compelling near-term economics for Fyto farms, reducing the payback period by approximately 50X. Given these exceptional margins, Fyto envisions providing opportunities for dairy producers to invest in these projects and receive dividends/royalties so that they would experience new revenue streams from these exported ingredient sales.

One of the most impactful cost reductions came from a redesign of Fyto's harvesting systems as shown in Figure 2. By shifting to off-the-shelf irrigation components and repurposed chassis electronics, Fyto reduced the bill of materials for major equipment by more than 67%, paving the way for more affordable deployment at scale. Additionally, by studying the labor requirements of various tasks on this first installation, the team determined that automating plant conveyance from harvest to central processing would dramatically reduce COGS. Provided this could be done without escalating CAPEX, the tradeoff would be well worth it.

Rather than focus on these high margin opportunities for the long run - as Fyto's mission is to help producers profit from rapid decarbonization of the food system - the team felt compelled to model out and test methods to best serve the broader dairy industry. As shown in Table 1 and Table 2, Fyto's team has mapped out strategies to arrive at $31,700 per acre capex and $127/ton dry matter for fresh lemna within the next few years. Recasting these numbers with a slightly improved yield that would be expected with multiple seasons of improved methods yields a 5–6-year payback:

$400 --	**$127**	**= $273**	**X 20 tons/acre**	**=$5460/ac per yr**
Current concentrate price	Fyto COGS 2030	Savings per ton with Fyto	Yield of Fyto per acre by 2030	Savings per year per acre with Fyto

$31,700 /	**$5460**	**= 5.8 years**
Projected CAPEX per acre by 2028	Savings per year	Simple payback

This is a much more compelling payback for the on-farm solution. If we also include a $50/ton CO2eq revenue stream and assume 2 tons CO2eq per ton dry lemna, the payback drops to 4.25 years. There are other IRR boosting mechanisms that could be evaluated including grants to offset a portion of the CAPEX or selling a fraction of lemna into higher value products, but there are also risks to this equation including the cost of capital, collapsing carbon markets, underwhelming yields, margin for Fyto sales, etc. Still, seeing a viable pathway to an unsubsidized 4–6-year simple payback with a system that could simultaneously solve major pain points in nutrient management and feed provision is believed to be very promising for the broader dairy industry.

CAPEX ($/acre)					
	2025	**2026**	**2027**	**2028**	**Capex Reduction Strategy**
Growing Environment	$26,000	$20,000	$13,400	$9,500	Larger growing environments lead to less wall and liner costs per acre, plus volume pricing
Nutrient Supply + Delivery	$5,900	$4,300	$4,300	$3,500	Less plumbing per acre with larger systems. Reduced pricing at volume
Harvester	$35,000	$26,000	$20,000	$10,600	Larger harvesters leading to more acres per machine
Downstream Processing	$5,500	$4,000	$2,500	$2,500	Economy of scale
Balance of System	$4,000	$3,000	$1,000	$300	Economy of scale
Infrastructure	$11,900	$10,000	$6,000	$3,800	Larger installations reduce per acre infra

					costs
EPC	$5,100	$2,500	$2,000	$1,500	More in-house EPC as more projects get built
Cost per Acre	$93,400	$69,800	$49,200	$31,700	

Table 8: Capex projections for Fytofarms through 2028

Cost of Goods for Fyto Lemna								
		2025	**2026**	**2027**	**2028**	**2029**	**2030**	**COGS Reduction Strategy**
Maintenance	$ / DM ton	$98	$39	$32	$29	$28	$27	Less moving parts, volume discount
Labor - Operations	$ / DM ton	$25	$8	$4	$4	$3	$3	Increased automation
Input - Growth Media	$ / DM ton	$178	$122	$96	$84	$77	$73	pH control optimization and volume discounts
Rent - Crop Acre Rent Expense	$ / DM ton	$48	$44	$41	$33	$20	$16	Higher yields and more perceived value by producer
Input - Electricity	$ / DM ton	$10	$10	$9	$8	$8	$8	Modest optimization over time
Total COGS - Fresh	**$ / DM ton**	**$359**	**$223**	**$182**	**$158**	**$136**	**$127**	
Drying and Pelleting Expense	$ / DM ton	$592	$329	$249	$248	$247	$247	Economies of scale
Total COGS - Dry Pellets	**$ / DM ton**	**$951**	**$552**	**$431**	**$406**	**$383**	**$374**	

Table 9: COGS projections for Fyto lemna (fresh and dry pellets) through 2030

Market and Regulatory Considerations

Separate from driving capex and cogs down, the company also conducted market and regulatory research to assess factors influencing adoption. Feed prices, nitrogen application pressures, and water availability were found to vary significantly even within the state. Fyto's value proposition is particularly strong in regions facing high input costs and/or tight regulatory limits on nutrient discharge or water use.

Feed Permissions

One of Fyto's largest hurdles has been in obtaining permission to feed animals lemna in California. Initial regulatory expert assessment and early conversations with CDFA suggested that, as a homegrown forage, lemna being fed on host dairies would not require a feed permit in accordance with CDFA Code §15051(c)(2). In seeking written approval to proceed, however, Fyto was told that it would need to go through the typical federal and state feed ingredient approval processes to proceed feeding animals in CA. As recommended by the FDA, Fyto submitted an AAFCO ingredient definition application in the Summer of 2024 but in the fall, AAFCO and FDA terminated their MOU, requiring Fyto to start over again. These delays not only affected Fyto's ability to serve dairies with much needed protein but also cast Fyto in a much less attractive light to investors who were excited by the technical progress and potential for impact at scale but nervous about the apparent regulatory risk. Additionally, this resulted in a large waste of resources since any of Fyto's high quality protein that could not be dried and stored had to be landfilled since it could not be given to animals.

Pivot to Fertilizer

As the feed permission process became a major protracted issue for Fyto, the team evaluated moving operations to another state with more clear permissions or to sell lemna into approved CA markets that weren't feed. Given the installed capacity at Rancho Teresita and interest and momentum to help dairies in California with nutrient management, the Company instead pursued lemna fertilizer product development while the feed permitting process was driven in parallel. The Company had previously commissioned an agronomic contract research organization in Southern California to explore use of lemna as an organic single ingredient fertilizer that could compete existing multi-ingredient incumbents. This contract research organization helped design and test dried lemna meal as the sole nutrient source for head lettuce. Dried lemna was applied at iso-nitrogenous levels to 4 leading organic fertilizers but was also tested at an 80% Nitrogen level to determine if less mass of lemna could be used to accomplish similar yields. As shown in Figure 8, the results of this experiment were very positive. The 80% nitrogen lemna meal significantly outperformed all of the existing commercial organic fertilizers in terms of lettuce yield. Additionally, nitrogen leaching rates were lower with both lemna conditions compared to the 4 other conditions.

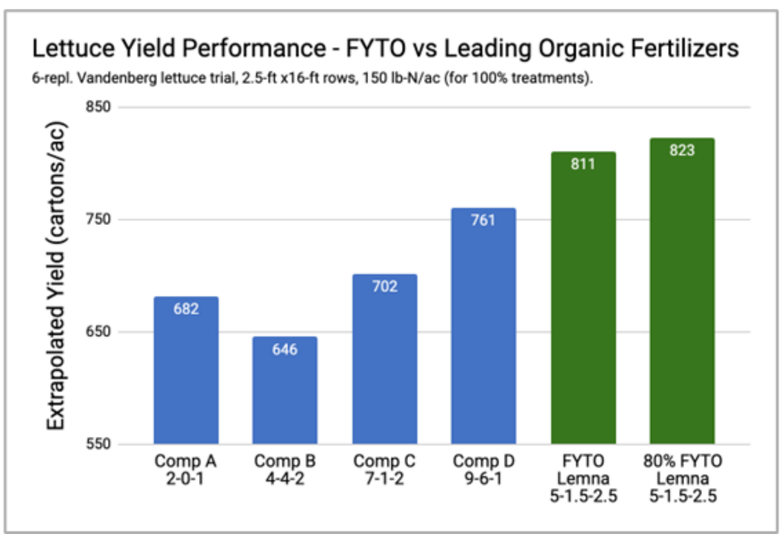


Figure 10: Lettuce yield with 4 existing organic fertilizers vs lemna meal at same and 80% nitrogen levels

Objective 6: Producer Engagement

Key Activities and Take-Aways

1. Fyto hosted a major Industry Outreach Day in September 2024 with over 100 dairy participants.
2. Fyto conducted 11 additional tours with major ag producers, technology developers, and global food brands, bringing several hundred individuals to the operation.
3. Fyto generated strong interest and insightful questions from dairy producers and industry stakeholders for lemna-based nutrient recycling and feed.

Summary:
Fyto prioritized engagement with dairy producers throughout the project to ensure relevance, transparency, and potential for future adoption. The centerpiece of this effort was a large-scale Industry Outreach Day hosted at the Tulare project site on September 9, 2024. Over 100 representatives from regional dairies attended to tour the farm, observe system demonstrations, and engage in technical discussions with Fyto's team. A video capturing this special event is available in Figure 11.

Figure 11: A video capturing the demo day in September 2024. Link: https://vimeo.com/1012452446?autoplay=1&muted=1&stream_id=Y2xpcHN8MTI3NDI3Nzk3fGlkOmRlc2N8W10%3D

Following this initial event, Fyto hosted a series of follow-on site visits with a diverse range of stakeholders, including industry groups, biogas partners, equipment manufacturers, and academic institutions. These engagements helped validate the broad industry interest in lemna as both a sustainable feed and a nutrient management solution.

Key Lessons from Producers
Producer interactions within the real-world installation of the Fytofarm was a highlight of this work. With dairy producers able to "kick the tires" of the system, view it in operation, and ask the Fyto team about how it worked and whether it could accommodate other conditions, there was a deeply valuable exchange that took place. One particularly interesting finding was that dairy producers were chiefly concerned with the same top

3 things but not necessarily in the same order: groundwater restrictions through the Sustainable Groundwater Management Act, associated nutrient management concerns and the potential need for herd size reduction, and reliable and affordable feed. Within these three areas, however, producers had different priorities and requests. Some saw protein production as the best benefit, others thought protein was solved by importing canola and instead were worried about how water policy would reduce corn silage acres and thus starch production for their animals. Some asked if Fyto could push the limit to have our system consume more digestate while some asked if Fyto could use less. In context, this all makes sense, given different operations have different herd counts, available land, and water. Several producers wanted to know what would happen in the winter months when Fyto's system would essentially hibernate. Even though Fyto's active growing season is longer than any dairy-relevant land crop in CA, the December through March hiatus presents challenges. Would producers need to buy protein concentrate for these months or oversize the Fyto system to dry some inventory for those months? Would nutrient management need to be handled differently since Fyto's crops would not be taking in any nutrients for 2-3 months? Another common question that was difficult to answer at this stage was how much the systems would cost. Fyto's long-term vision was that producers would own and operate their own lemna facilities and Fyto would provide the equipment, software, start plants, and know-how to make everything run smoothly. Until the capex and COGS numbers were driven down, however, Fyto anticipated building, owning, and operating the systems.

Figure 12: The Fyto September 2024 Demo Day included sign-up sheets, informational handouts, and a Q&A session to answer producer questions about the process

Figure 13: Throughout the operation of the project, Fyto hosted hundreds of producers and dairy stakeholders from around the world. Pictured here is a group of member relations representatives from one of the largest dairy cooperatives in the US.

Results and Discussion

Fyto's CLIM3ATE-funded project successfully proved the technical feasibility of large-scale lemna (duckweed) cultivation on California dairies using only anaerobic digester effluent as a nutrient source. Over the project period, the system at Rancho Teresita achieved stable operations at a 3.3-acre scale, harvesting more than one million pounds of fresh biomass. Yields in certain sections averaged the equivalent of ~15 dry tons per acre per year under optimized management, with consistent nutritional quality exceeding 35% crude protein (dry weight) and high total digestible nutrients. Frequent monitoring of water chemistry and plant health allowed the team to refine best practices for pH, nutrient concentration, and harvesting frequency, resulting in improved productivity and operational efficiency.

Environmental performance was a key outcome of the project. Independent air quality measurements demonstrated that lemna cultivation emitted substantially lower greenhouse gas emissions compared to conventional wastewater lagoons and corn silage fields. Screening-level life cycle assessment indicated that replacing canola meal with Lemna in dairy diets could reduce feed-related GHG emissions by nearly 80%, equivalent to 2–3 tCO_2e mitigated per dry ton of Lemna produced. Additional nitrogen balance studies showed that the system could achieve nitrogen use efficiencies above 90% under certain conditions, providing a powerful nutrient management tool for dairies facing regulatory and environmental pressures.

Animal feeding trials and an expert GRAS panel continue to validate the safety and efficacy of lemna as a feed ingredient. Independent studies by Pennsylvania State University found no safety concerns and observed positive effects on animal growth and feed efficiency in both sheep and broiler chickens. They are currently conducting a dairy cow feeding trial with material from this project. Heavy metal, mycotoxin, and pesticide testing confirmed that all measured contaminants were within safe limits or below detection. While dairy cow feeding trials are ongoing, these early results support lemna's potential as a high-value, protein-rich forage option for multiple livestock sectors.

Economic analysis revealed both promise and current challenges. Near-term payback periods for on-farm feed replacement remain unattractive without capital offsets, carbon revenue, or premium markets. This was an expected result on the first commercial scale system. However, design innovations—particularly in harvesting automation and use of off-the-shelf components—are projected to cut capital costs by more than two-thirds and would reduce operating costs significantly by 2028. Under modeled future scenarios, payback periods could fall to 4–6 years without subsidies, especially if paired with carbon credit revenues or partial sales into specialty ingredient markets.

Producer engagement throughout the project underscored strong industry interest but also highlighted diverse operational priorities—ranging from groundwater restrictions and nutrient management to feed reliability and cost. Many producers expressed enthusiasm for lemna's potential but sought clarity on winter-season operations, digestate handling capacity, and long-term economics. These conversations reinforced that a flexible deployment model, tailored to farm-specific constraints, will be essential for widespread adoption. Overall, the project validated lemna cultivation as a climate-smart, nutrient-recycling, and high-protein production system with significant potential to transform manure management and feed production on California dairies.