Biofertilizer Economics and Environmental Impact

Tyler Barzee, PhD

Assistant Professor

Department of Biosystems and Agricultural Engineering

University of Kentucky

California Bioresources Alliance Symposium

November 19, 2021

tjbarzee@uky.edu

College of Agriculture, Food and Environment

Biosystems and Agricultural Engineering

100 YEARS 1915 - 2015 UCDAVIS BIOLOGICAL AND AGRICULTURAL ENGINEERING

Acknowledgements

- **Coauthors:**
  - Abdolhossein Edalati
  - Hamed El-Mashad
  - Bryan Jenkins
  - Josh Rapport
  - Ruihong Zhang
- UC Davis Bioenvironmental Engineering Lab Members
- **Funding:** California Department of Food and Agriculture

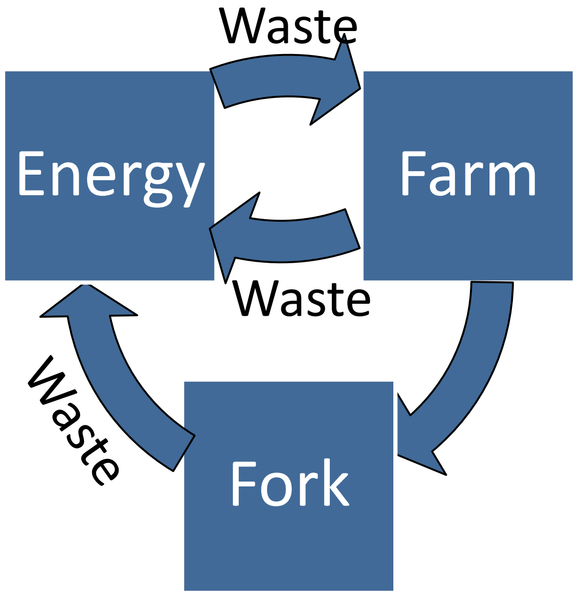
National Academy of Engineering Grand Challenges in the 21st Century

Common Connection:

Waste Utilization and Management

https://www.deere.co.za/en_US/products/equipment/nutrient_application/nutrient_applicators/2510l/2510l.page
https://www.livescience.com/42242-who-blame-for-climate-change.html
(Craggs et al., 2014)
http://zeenews.india.com/news/sci-tech/salt-degraded-farm-soil-now-equals-the-size-of-france_1490750.html

Anaerobic Digestion and Digestate



Anaerobic Digestion

- Microbes break down organic matter and create biogas
- Biogas ~ 60% CH_4 and 40% CO_2
- Biogas used for energy production
    - Potential to avoid CH_4 and N_2O emissions from landfilling or anaerobic lagoons [1]
- Nutrient rich effluent (digestate)

Digestate as fertilizer

- Suitable for many applications?
- Reduce environmental impacts?

UC Davis Renewable Energy Anaerobic Digester [2]

Digestate

Raw Digestate Characteristics (mg/L)

Parameter	Dairy manure digestate	Food waste digestate
TS	37,000	50,000
EC *(dS/m)*	14.4	22.4
TKN	2,142	4,037
NH_4-N	1,075	2,286
P	422	490
PO_4-P	12.3	52.1
Cl	1,397	1,379
K	2,180	1,692
Ca	879	887
Mg	571	266
Na	522	958

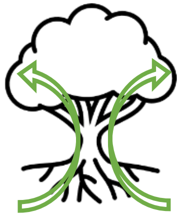
[1] (Montes et al., 2013)
[2] http://photos.ucdavis.edu/viewphoto.php?imageId=9482480

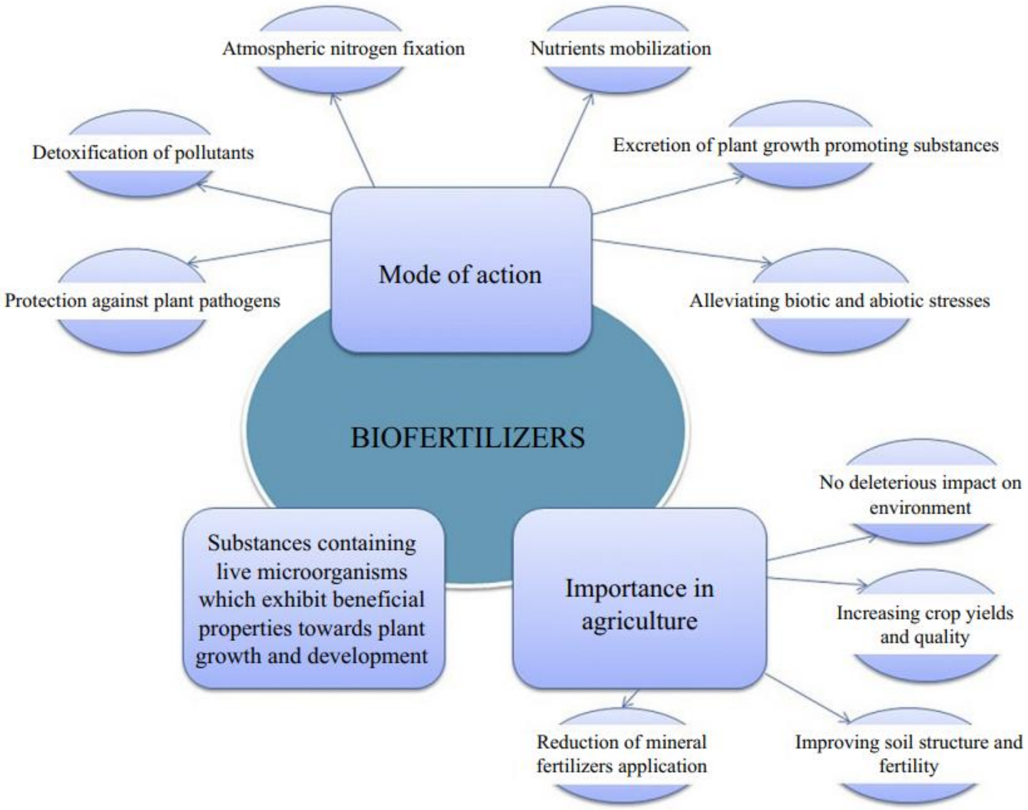
Introduction to Biofertilizers

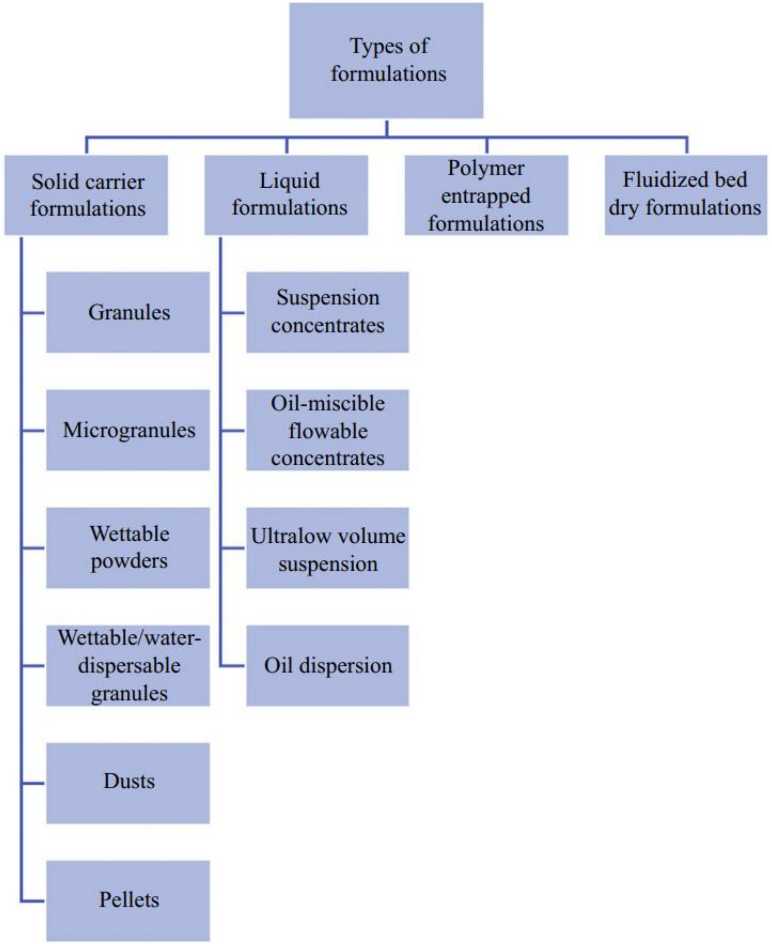
Biofertilizer

Biological

Nutrition







Mącik, M., Gryta, A., & Frąc, M. (2020). Biofertilizers in agriculture: An overview on concepts, strategies and effects on soil microorganisms. In *Advances in Agronomy* (Vol. 162). https://doi.org/10.1016/bs.agron.2020.02.001

https://microbiologysociety.org/why-microbiology-matters/what-is-microbiology/fungi.html
Dennis Kunkel Microscopy / Science Photo Library

Biofertilizer Microbes and Market

Common Biofertilizer Microbes

- Nitrogen Fixing
  - *Rhizobium* spp.
  - *Azospirillum* spp.
  - *Azobacter spp.*
- Phosphorus Solubilizing and/or Mobilizing
  - *Pseudomonas* spp.
  - *Agrobacterium* spp.
  - *Bacillus circulans*
  - *Penicillium* spp.
  - Arbuscular mycorrhiza fungi
- Potassium Solubilization
  - *Bacillus* spp.
  - *Frateuria aurantia*

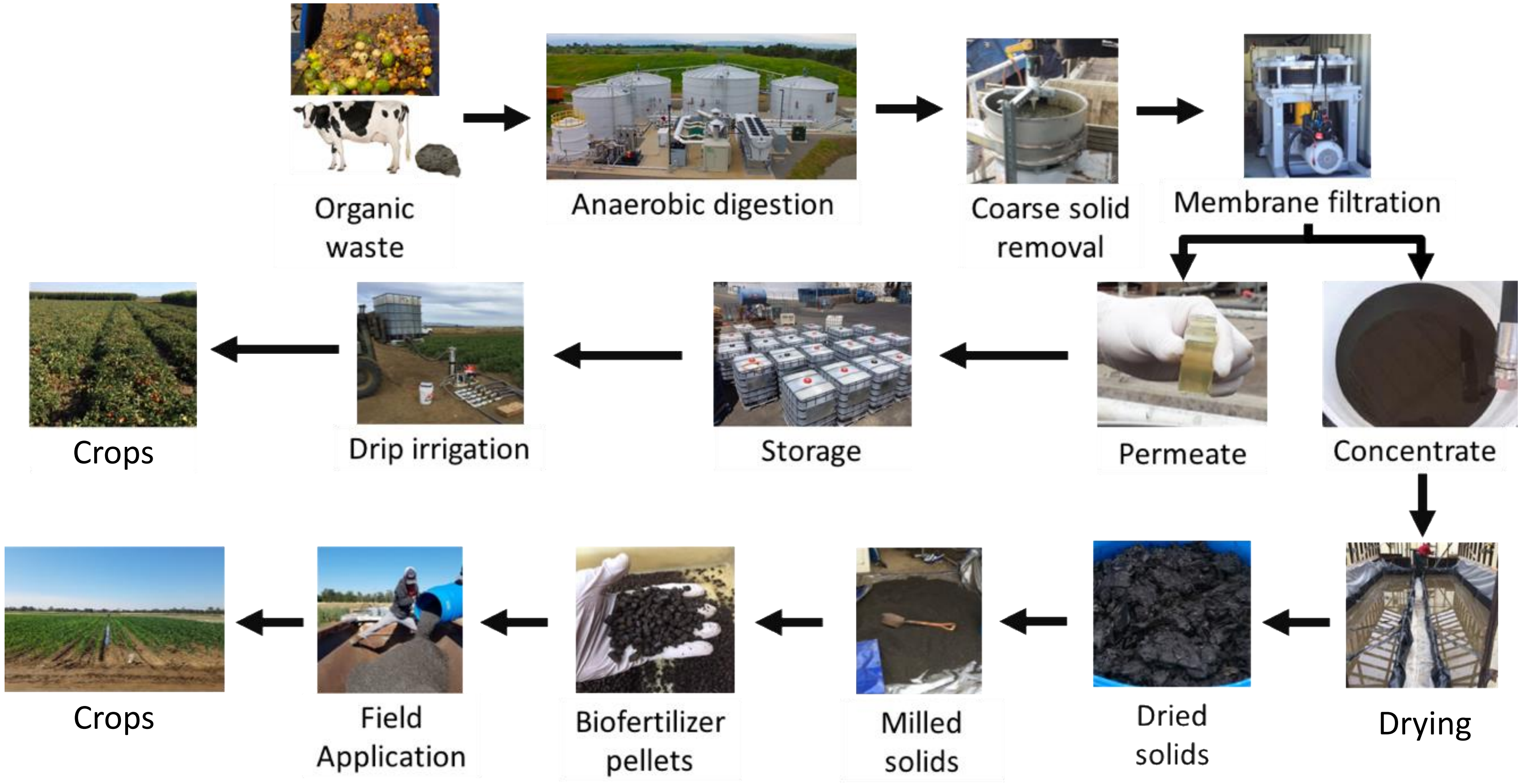
Digestate often contains several genera of plant growth-promoting microbes

(Mącik et al., 2020)

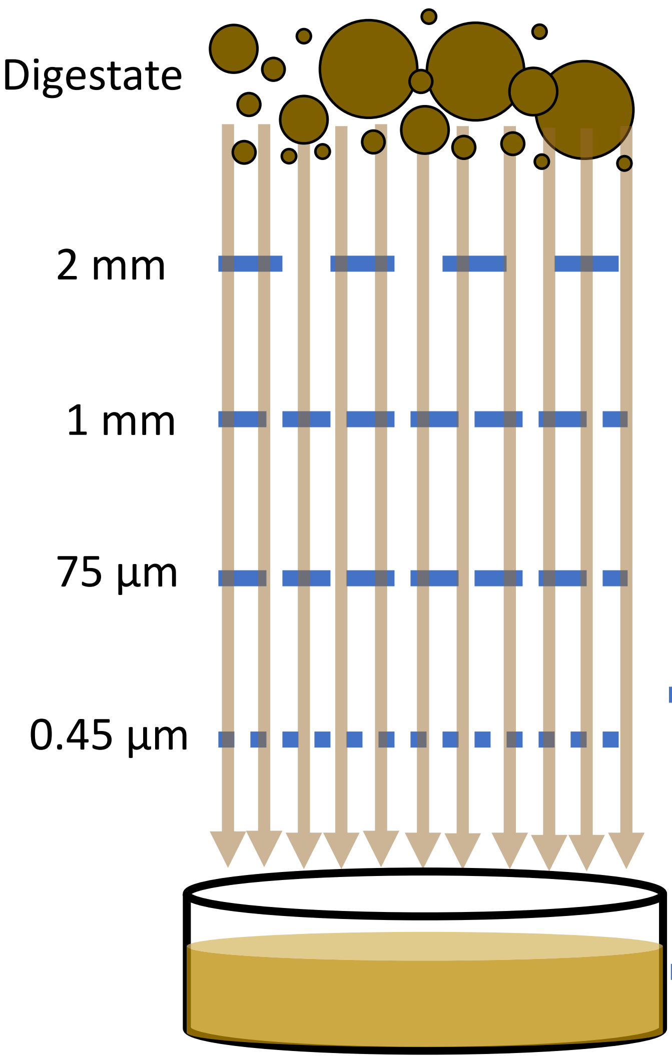
Market prices for various solid/liquid organic and inorganic fertilizers

Main Ingredients	N (%, w.b.)	P (%, w.b.)	K (%, w.b.)	Cost ($/ lb NPK)	Reference
Inorganic nutrients	20	4.4	16.6	**3.42**	(Mattson, 2010)
Fish hydrolysate + kelp	4.0	1.7	0.4	**44.39**	
Seed extract	3.0	0.4	0.8	**30.50**	
Seed extract + Inorganic nutrients	10	1.7	2.5	**6.10**	
Fish hydrolysate	2.3	1.5	0.8	**13.60**	Seven Springs Farm Organic Farming & Gardening Supplies LLC
Poultry Manure compost	5.0	1.7	2.5	**4.17**	
Poultry Manure compost	5.0	1.7	2.5	**3.17**	
Poultry Manure compost	5.0	1.7	2.5	**4.65**	
Digestate Pellet	3.7	0.4	3.6	**0.75**	(Dahlin et al., 2015)
Bone meal	4.0	6.1	0.0	**10.19**	Peaceful Valley Farm Supply, Inc.
Guano	12	5.2	2.1	**3.85**	
Feather and Bone Meal	7.0	2.2	5.8	**6.56**	
Feather Meal	4.0	1.7	1.7	**2.06**	Agricultural Supplier Quote
Meat and Bone Meal	8.0	2.2	0.8	**3.09**	
Feather and Bone Meal	10	2.2	1.7	**3.21**	
Feather Meal	12	0.0	0.0	**4.38**	
Urea-Ammonium-Nitrate	32	0.0	0.0	**0.99**	(Quinn, 2019)

Pilot Production and Application of Digestate Biofertilizers



Designing Digestate Biofertilizer Products

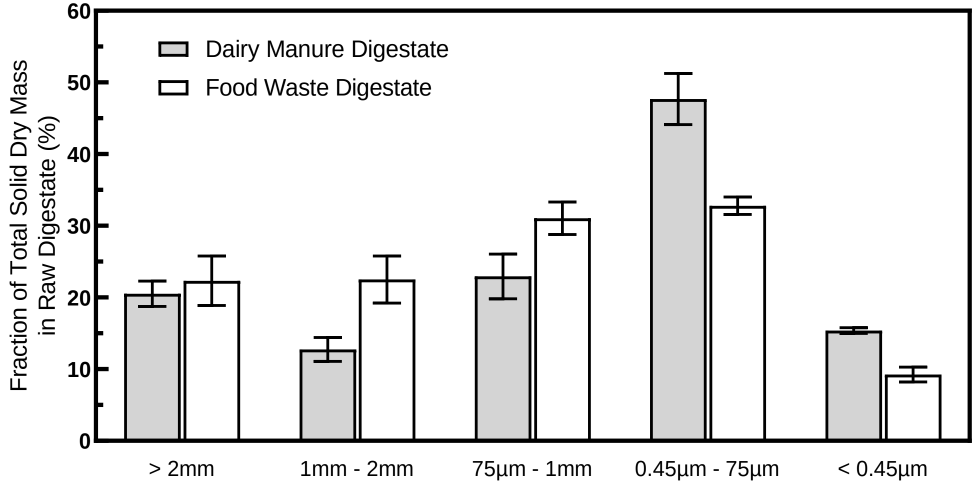


Analyses

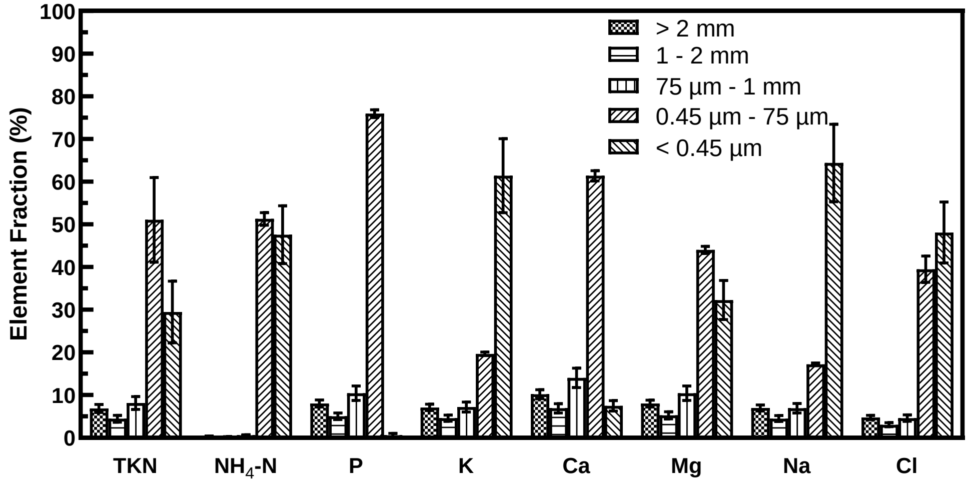
Wet Mass
TS/VS

Nutrients/Salts
- Total N
- NH4-N
- K
- P
- Na
- Cl
- Ca
- Mg

Particle Size Distribution



Nutrient and Element Distribution



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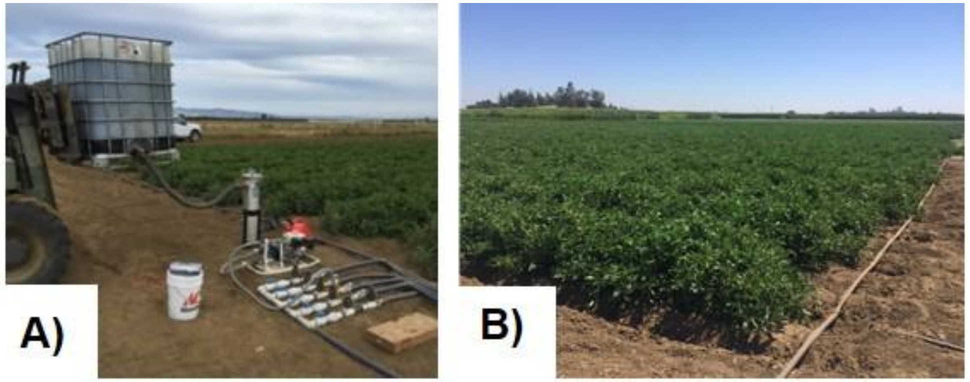
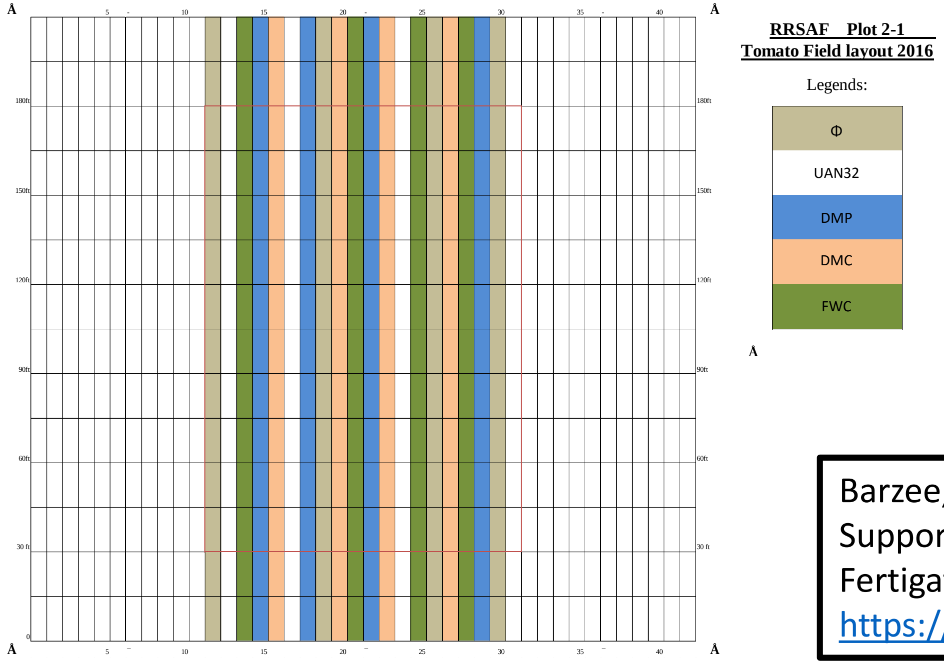
Field Evaluation of Crop Performance

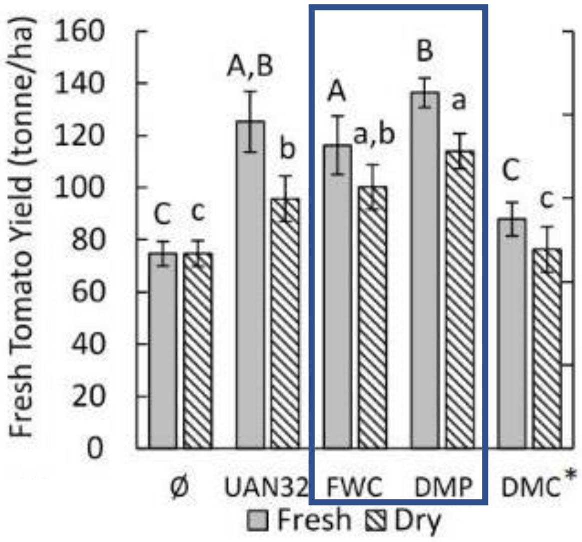
Biofertilizer Injection to Processing Tomatoes

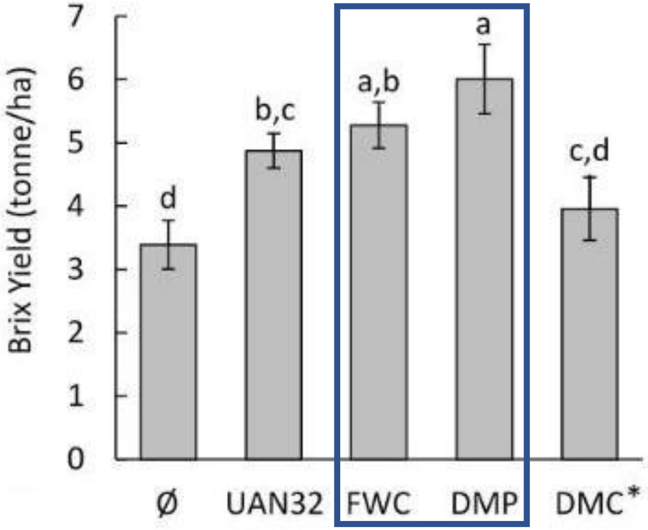


Field Experimental Design



Similar or Greater Yields Compared to Mineral Fertilizer





Φ – No Fertilizer
UAN32 - Synthetic Fertilizer
DMP – Ultrafiltered Dairy Manure Digestate
FWC – Concentrated Food Waste Digestate
DMC – Concentrated Dairy Manure Digestate

Barzee, T. J., Edalati, A., El-Mashad, H., Wang, D., Scow, K., & Zhang, R. (2019). Digestate Biofertilizers Support Similar or Higher Tomato Yields and Quality Than Mineral Fertilizer in a Subsurface Drip Fertigation System. *Frontiers in Sustainable Food Systems*, *3*. https://doi.org/10.3389/fsufs.2019.00058

Research Goal and Objectives

Research Goal: Determine the characteristics and required breakeven sale price of solid and liquid digestate biofertilizer products produced by an integrated processing system.

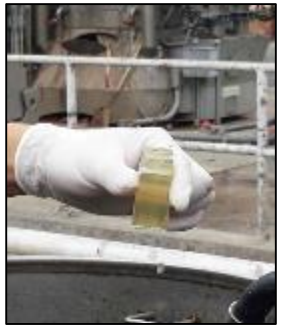
Objectives:

1. Conduct pilot-scale mechanical separation and membrane filtration to produce liquid and solid fertilizer products from food waste and dairy manure digestates.

2. Perform an economic analysis of digestate biofertilizer production from similarly designed processing systems at digesters of different capacities.

Biofertilizer Nutrient Compositions

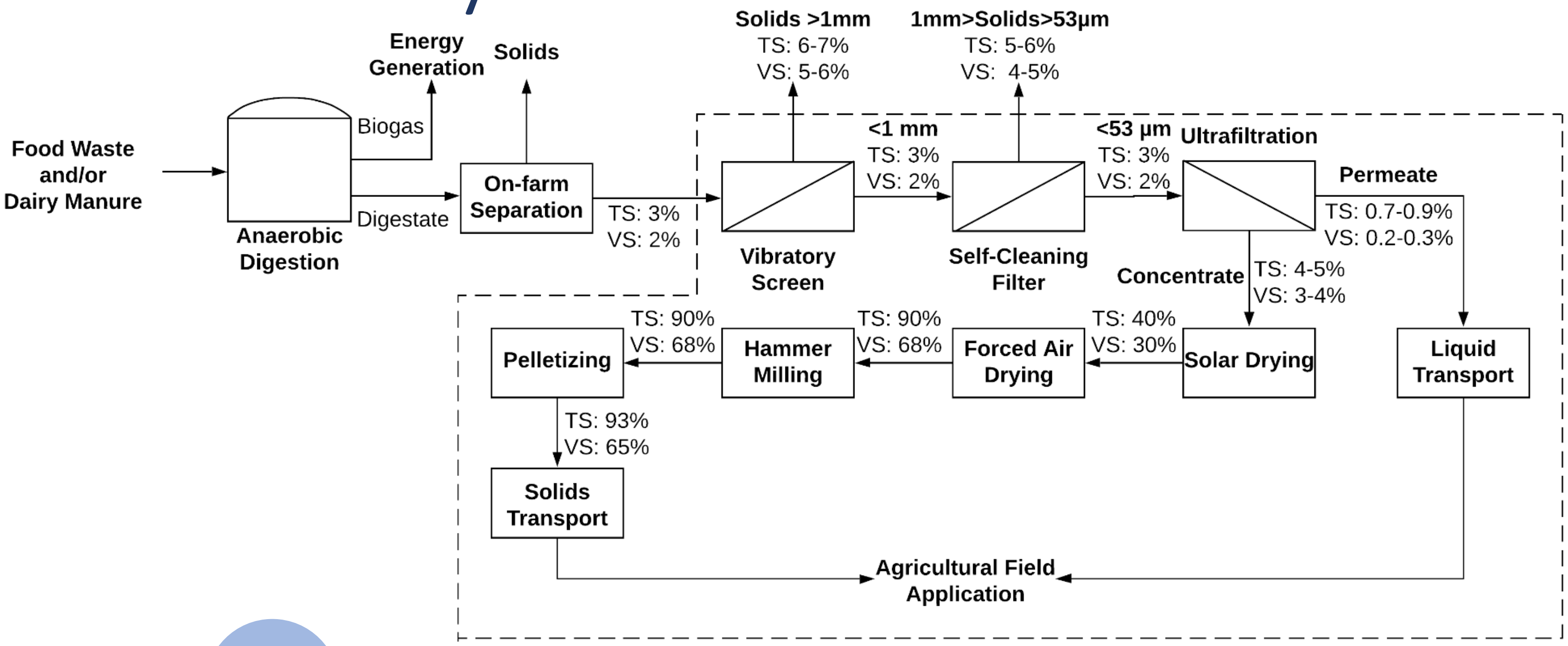
Parameter	Ultrafiltered Food Waste Digestate (mg/L)	Ultrafiltered Dairy Manure Digestate (mg/L)	Food Waste Digestate Pellet (% w.b.)	Dairy Manure Digestate Pellet (% w.b.)
N	2,710 ± 127	1,675 ± 7	5.07	3.74
NH_4^+-N	2,340 ± 141	1,470 ± 14	-	-
Organic Matter	-	-	20.13	33.2
P	18.4 ±2.3	5.1 ± 1.7	1.66	1.36
K	1,710 ± 28	1,670 ± 42	2.26	3.12
Na	819 ± 13	610 ± 9	1.13	0.67
Ca	5.93 ± 1.31	5.3 ± 0.4	3.57	2.99
Mg	8.38 ± 3.85	161 ± 15	0.35	1.66

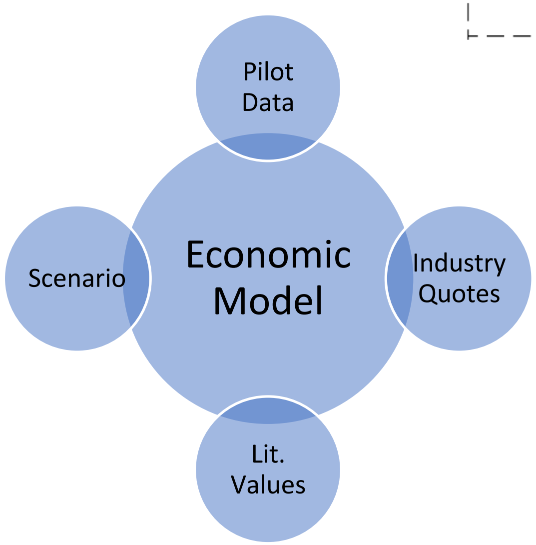


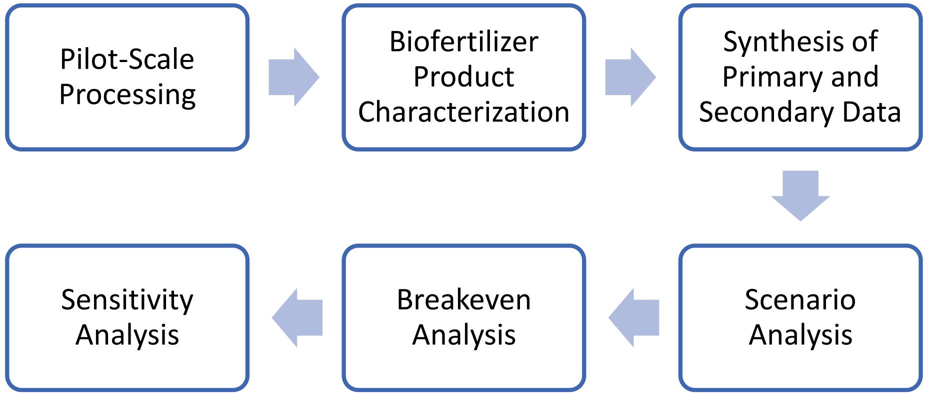

Ultrafiltration Permeate and Concentrate

Pellets

Processing System and Economic Analysis System Boundary







Economic Model

Inputs → **Model** → **Outputs**

Inputs

System Capacity
Capital Cost
Operating Cost
Discount Rate
Land Lease
Energy Cost

Model

General Model

$$A = P\left(\frac{i(1+i)^n}{(1+i)^n-1}\right)$$

$$\frac{C_P}{C_o} = \left(\frac{M_p}{M_o}\right)^s$$

$$TAC = A + O_C$$

$$S_P = \frac{TAC}{M_P}$$

A = Annuity ($/yr)
P = Present Sum ($)
i = Interest Rate (%)
n = Compounding Periods
C_P = Capital Cost ($)
C_o = Reference Capital Cost ($)
M_P = Capacity (kg/yr)
M_o = Reference Capacity (kg/yr)
O_C = Operating Cost ($/yr)
TAC = Total Annual Cost ($/yr)
S_P = Selling Price ($/kg)

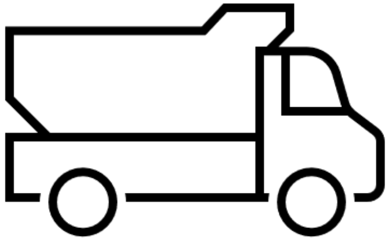
Outputs

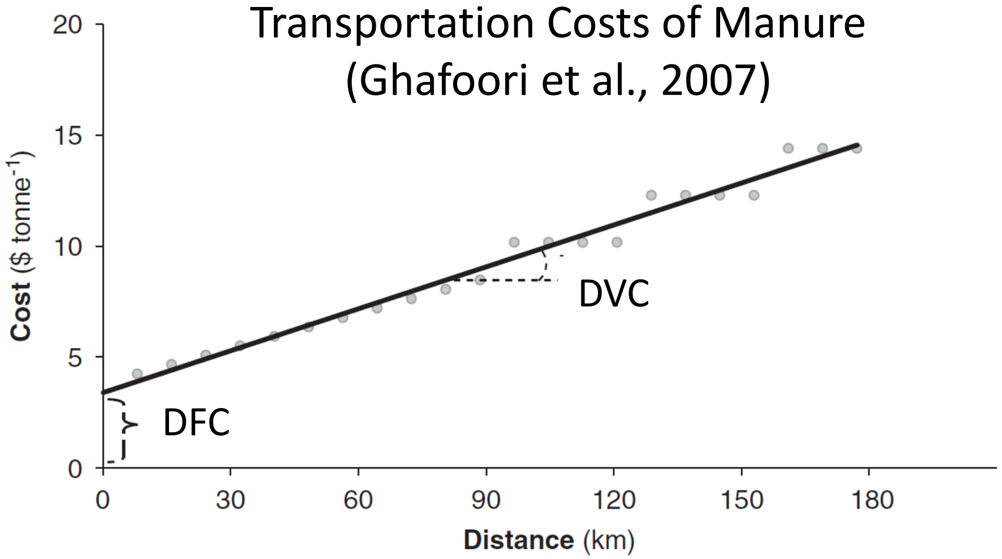
Biofertilizer Selling Price ($/kg)

Notes:
- Digester and processing system co-located
- Four months per year, active drying exclusively used
- Main product is pellets, liquid (permeate) sold at cost of transport

Transportation

- DFC – Distance Fixed Cost
- DVC – Distance Variable Cost
- Regional Dependency





Liquid DFC ($/tonne)	Liquid DVC ($/tonne-km)	Solid DFC ($/tonne)	Solid DVC ($/tonne-km)	Region	Source
11.17	0.09	-	-	Europe	(Drosg et al., 2015; Josef Bärnthaler et al., 2008)
4.57	0.37	-	-	US (Midwest)	(Brenneman, 1995)
2.96	0.28	-	-	US (East Coast)	(Aillery et al., 2005)
-	-	14.80	0.10		
2.96	0.28	8.89	0.13	US	(Ribaudo et al., 2011)
5.26	0.11	-	-	Canada	(Ghafoori et al., 2007)
5.40	0.09	5.40	0.09		
6.01	0.14	-	-	Europe	(Fuchs and Drosg, 2013b)
0.58	0.16	-	-	Europe	(Drosg et al., 2015)
19.19	0.05	-	-	**US (West Coast)**	This study
11.55	0.09	5.35	0.04		This study
15.37	**0.07**	**5.35**	**0.04**		**Used in this study**
5.68	**0.12**	**5.40**	**0.09**	**Europe/Canada (Average)**	**Used in this study**

Model Inputs

Input Category	Value	Unit	Source
Discount Rate	8	%	[1]
Capital Cost Economic Scale Factor	0.52	unitless	[2]
Operating Cost Economic Scale Factor	0.82	unitless	[2]
Loan Term	20	a	[1]
Electricity Cost [a]	0.13	$/kWh	[3]
Natural Gas Cost [a]	7.15	$/MM BTU	[4]
Land Lease	647	$/ha	[1]
Concrete Pad Cost	394,408	$/ha	[5]
Sun Drying Time	10	d	[7]
Sun Drying Loading	77	L/m^2	[7]
Sun Dryer Loading Depth	7.6	cm	[7]
Initial TS of Food Waste Digestate	5	%, wb	[6]
Initial TS of Dairy Manure Digestate	3.7	%, wb	[6]
Final TS from Solar Drying	40	%, wb	[6]
Final TS from Active Drying	90	%, wb	[6]
Operational time of Hammer and Pellet Mills	8	h/d	[1]
	260	d/a	[1]
Labor (one operator)	70,000	$/a	[1]

Source Legend*
[1] (Kaffka et al., 2016)
[2] Calculation from primary data
[3] (U.S. Energy Information Administration, 2019)[a]
[4] (U.S. Energy Information Administration, 2019)[a]
[5] (CSBOE, 2019)
[6] Primary Data
[7] (Barzee et al., 2021)[b]

[a] California, industry rate
[b] Loading based on primary data in Davis, CA

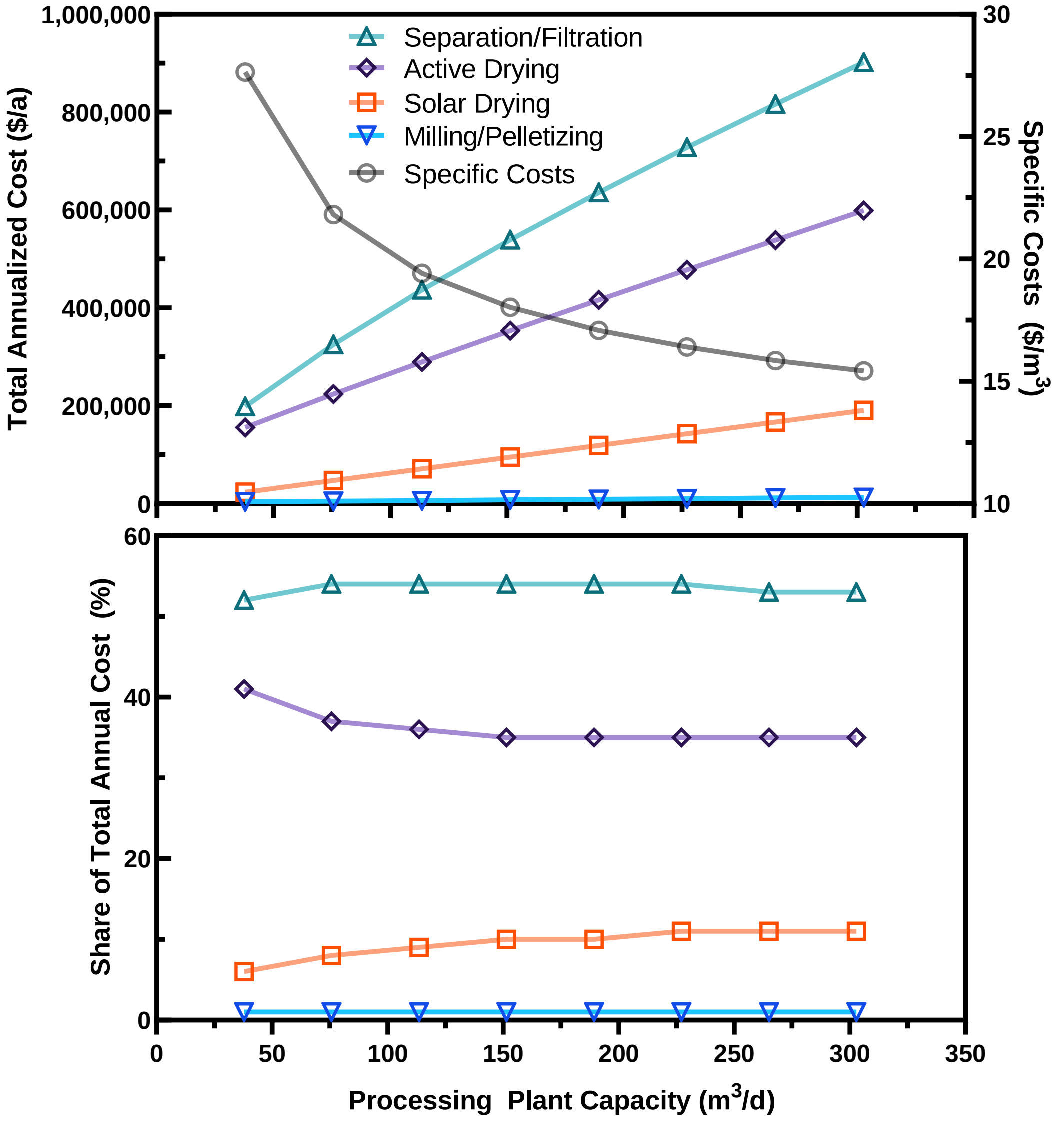
Capital and operating costs for a digestate processing system designed to process 10,000 gallons per day (base case)

Category		Capital Costs ($)	Operating Costs ($/yr)
Solid-Liquid Separation and Filtration	Storage and Processing Tanks	97,335	5,250
	Pumps	4,589	1,234
	Solid-Liquid Separation System	86,100	3,021
	Membrane Filtration System	**367,878**	**94,256**
	Controls, Valves, Flowmeters, Piping, and Fittings	10,420	1,575
	Electrical, Plant Design, and Installation	193,591	15,731
Solar Drying	Land Rent*	-	3,867
	Concrete Pad*	196,511	-
Active Drying	**Active Drying System**	**338,143**	**118,444**
Hammer Milling and Pelletizing	Hammer and Pellet Mills	17,736	2,507
Total		1,312,303	245,885

* 0.50 ha concrete drying pad, 10 day retention time, 8 months per year

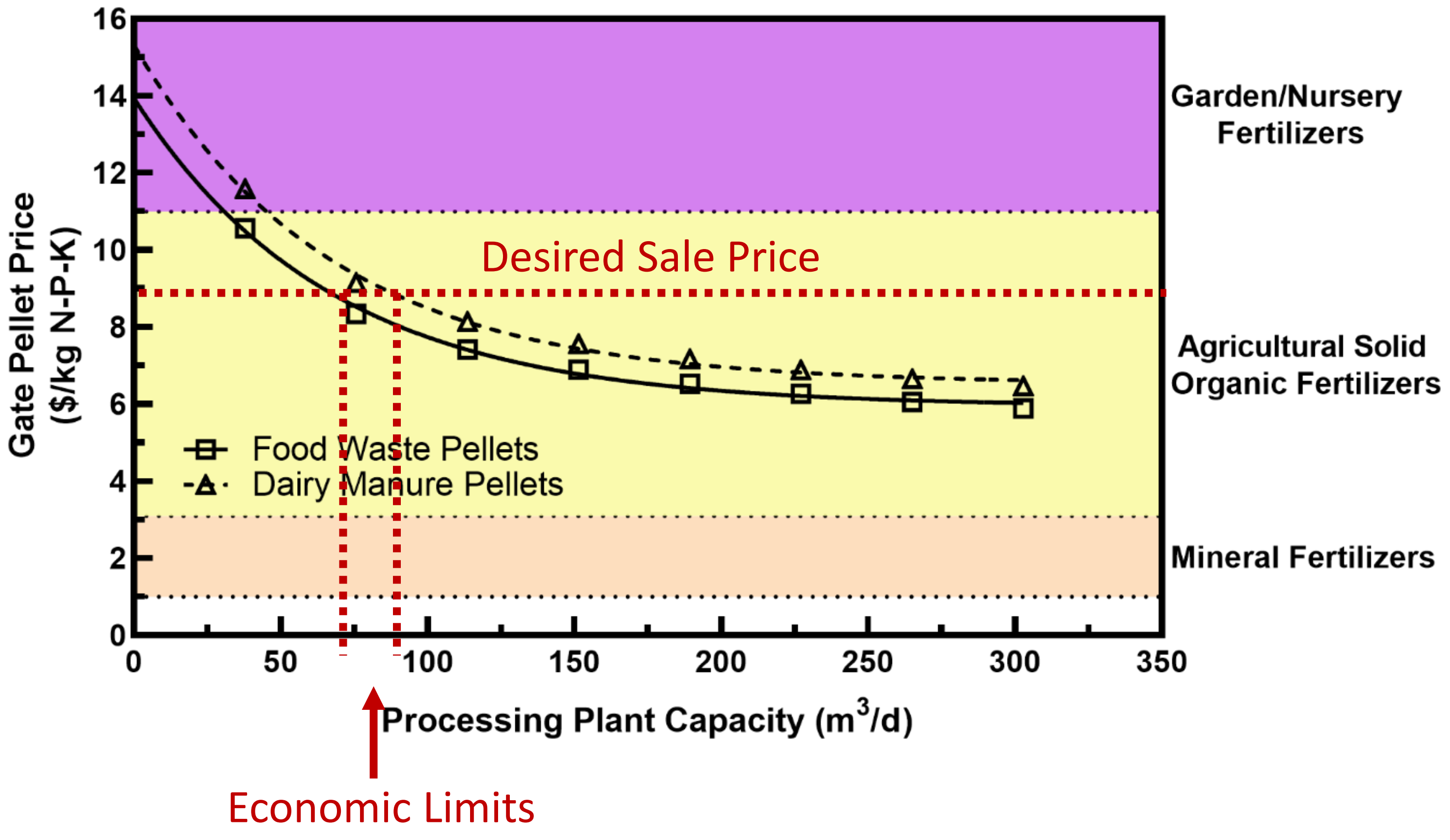
Results
Costs for Various Capacities

- Range of specific costs
  - **15-25 $/m³ (0.06 – 0.09 $/gal)**
  - Economies of scale
- Separation/Filtration and Active Drying make up ~ 80% of TAC
- Solar drying is economical but not applicable to all climates
- Milling/pelletizing may require extra conveying/cooling/packaging equipment not included in model



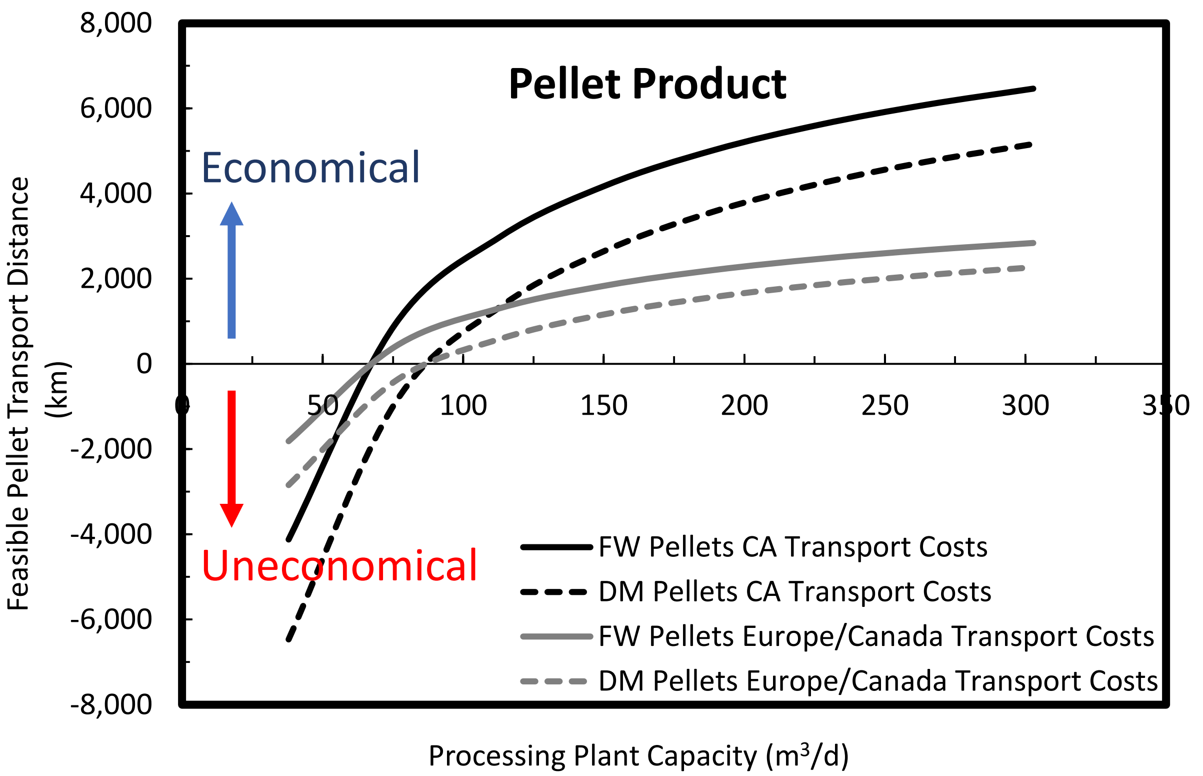
Results
Breakeven Pellet Sale Prices (at Gate)

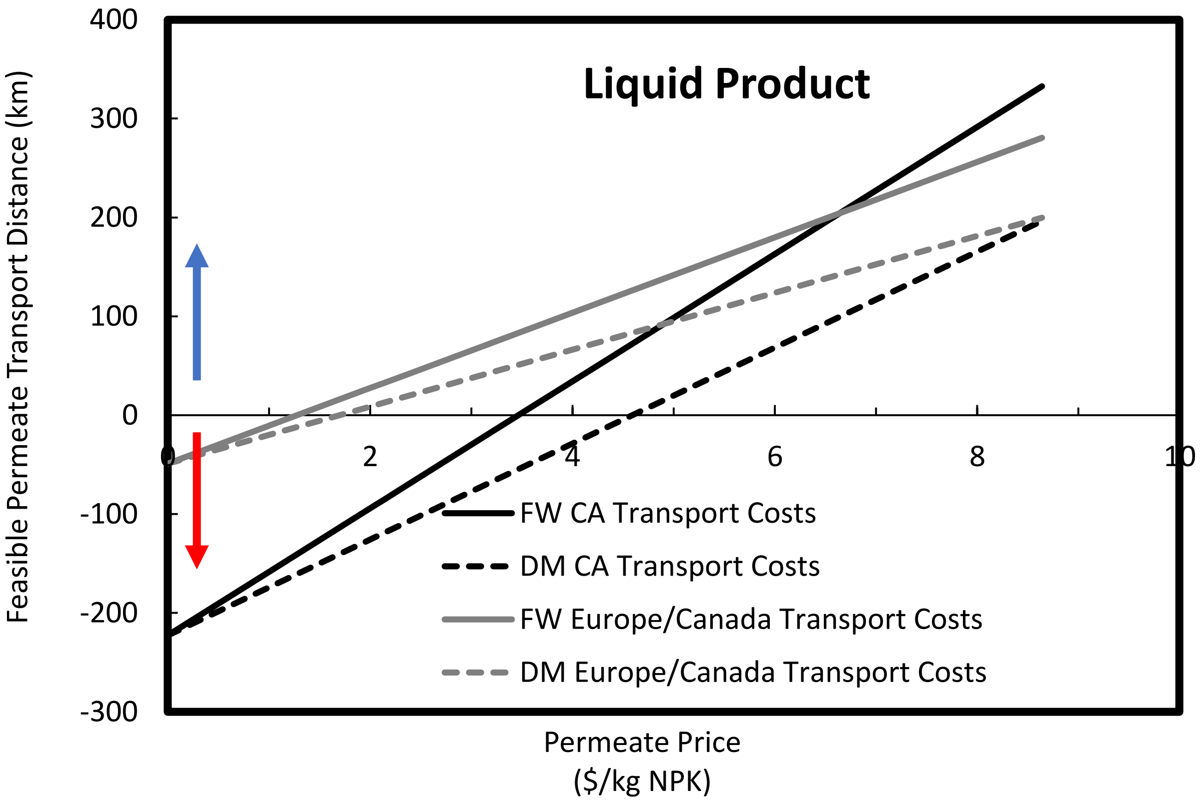
- Breakeven Prices
  - **6-11 $/kg NPK (3-5 $/lb NPK)**
  - Similar to CA ag market
- Dairy manure digestate
  - Lower nutrient contents → Higher required price
- Smaller scales might be constrained to garden market
- Diminishing returns for capacities > 100 m^3/d



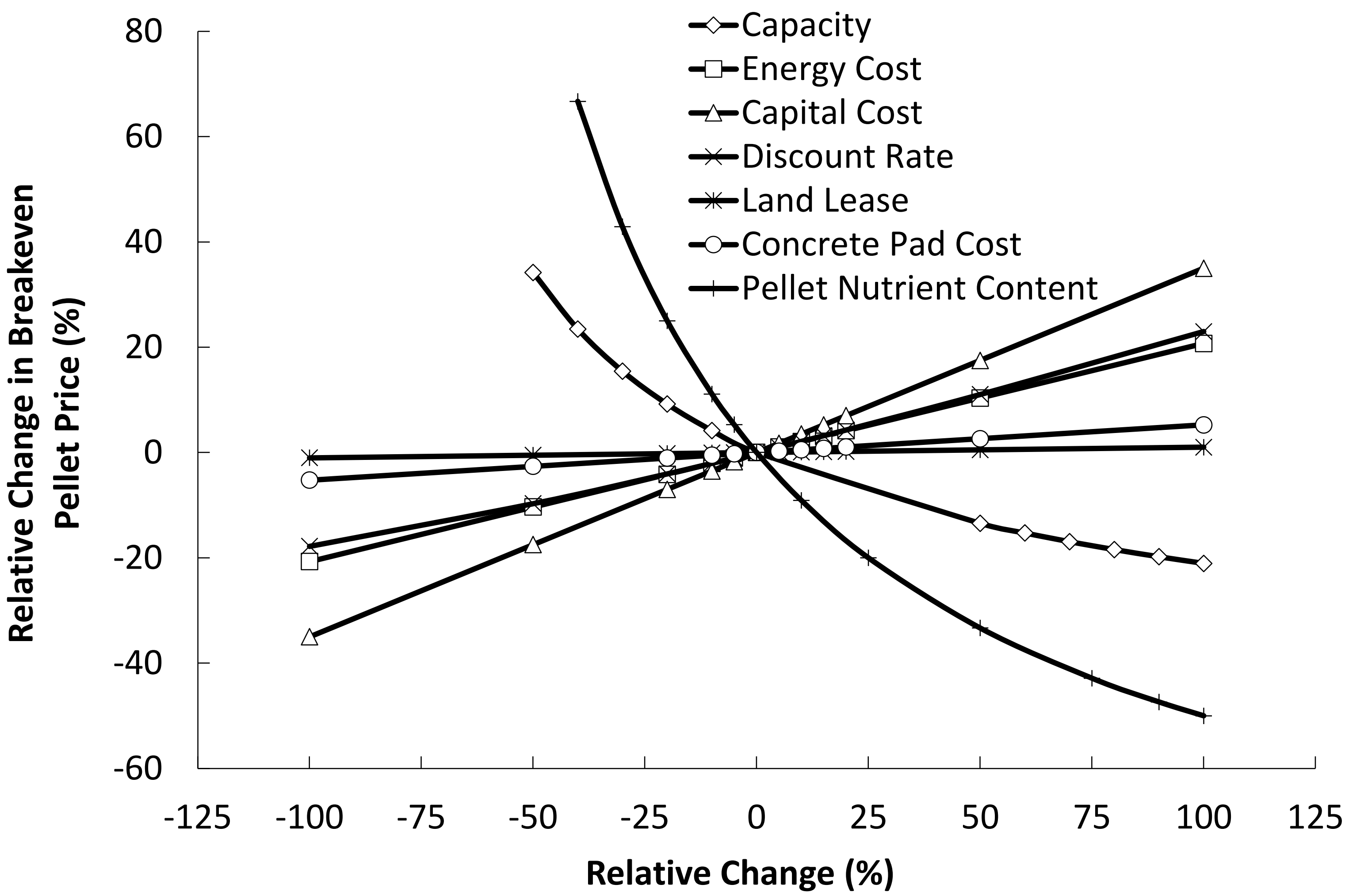
Results
Transportation and Sensitivity

- Pellets can be economically transported much farther than liquids
- Small-scale systems must increase sale prices to breakeven
- Liquids likely must be sold at prices **> 1 – 4.3 $/kg NPK** to justify transportation off-site





Results
Pellet Price Sensitivity Analysis



High Sensitivity:

- Nutrient content
- Plant capacity
- Capital cost

Low Sensitivity:

- Land lease rate
- Concrete pad cost

Optimize process by: increasing nutrient content of fertilizer, utilizing adequate scale and decreasing capital costs

Potential Environmental Impacts

- Fertilizer Production GHG Emissions
  - 4% of total anthropogenic emissions in 2007 (575 million tonnes $CO_{2,e}$)
  - Ammonium nitrate (synthetic fertilizer) USA average:
    - **7.5 kg $CO_{2,e}$/kg N at plant gate**
- Energy Production Emissions
  - CA Grid: **23.3 g $CO_{2,e}$/MJ electricity**
  - UC Davis Renewable Energy Anaerobic Digester (READ):
    - **5.39 g $CO_{2,e}$/MJ electricity**
    - **1.6 kg $CO_{2,e}$/kg N** *(note: estimate based on available N, full LCA needed)*
- Nutrients and Soil
  - Opportunities to export nutrients farther, reduce nutrient loadings in sensitive areas
  - Supplement synthetic fertilizer use, build healthy soil

Conclusions

- Pelletized biofertilizers contained **8.8 - 9.4% NPK (w.b.)**
- Total Annualized Cost range: **15-27 \$/m^3 for capacities 38 – 300 m^3/d**
- Breakeven pellet sale price range: **5.9 – 11.6 \$/kg NPK**
- Solid products can be economically transported much farther than liquid products
- Liquid product breakeven price must be **3.5 – 4.6 \$/kg NPK** to justify transportation
- Digestate biofertilizers potentially offer significant GHG reductions compared to synthetic fertilizers

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Thanks! Questions?

Contact:

tjbarzee@uky.edu
https://www.barzeelab.com

SCAN ME

Dr. Tyler Barzee