Module 8: Nutrient Management

8.1: Introduction to macro- & micronutrients

8.2: Nitrogen

8.3: Phosphorous

8.4: Potassium and other nutrients

8.5: Solid & liquid nutrients produced by AD

8.6: Environmental hazards & the case for nutrient separation

8.7: Phosphorous separation strategies

8.8: Nitrogen separation strategies

8.9: Salt removal & clean water technologies

8.10: Soil nutrients & soil health

8.11: Creation & implementation of cNMP

8.12: Data collection, reporting & compliance

This curriculum is adapted from: eXtension Course 3: AD, University of Wisconsin

8.5: Solid vs. liquid nutrients produced by AD

Separation of solids is very common

The solids content of a AD effluent depends on several factors:

1. The solids content of the feedstock
2. The efficiency of the AD technology & operations
3. The HRT

Why spend the money to separate solids?

- Separated solids are a valuable co-product used for:
  - Bedding
  - Composting
  - Soil amendment (fertilizer)
- Separation decreases the volume of effluent that must be stored in ponds over the winter.
- Solids sequester some phosphorous from effluent, creating a reduced phosphorous effluent that can be applied to phosphorous-rich fields.

Separation technologies

The most common method of separating solids is the **screw-press auger**.

- Effluent is pumped into the separator;
- An auger pushes the effluent against a cylindrical perforated screen;
- Squeezing liquid effluent out; and
- Pushing solids forward and out the end as a moist cake that drops out of the separator.

Solids are generally ~65% moisture.

Treatment & uses of solids

Separated solids may be used as bedding or soil amendment without any treatment. However, solids may be:

- Composted;
- Pasteurized; or
- Further dried prior to use.

Some moisture is helpful to keep solids from becoming too dusty. Here at the college, herd managers like to spread solids out in a 6 – 12" deep layer to dry a bit prior to use in as bedding.

If solids are stored in piles without composting, the pile will **heat up significantly** as composting begins.

Extensive studies conducted at Cornell show that there is **no significant difference in herd health and mastitis** when dairy cattle are bedded on separated solids before or after composting.

See module _____ for details of using separated solids as bedding.

8.6: Environmental hazards of nutrients & the case for nutrient separation

N & P: blessing or curse?

N & P are present in abundance in AD effluent. While they are a blessing for farmers, their abundance can be a problem if they are not used appropriately and accumulate in ground and surface water.

If significant concentrations of nitrogen & phosphorus reach surface waters they will fertilize tremendous growth of algae and plant life, causing **eutrophication:**

Excess nitrogen in water used for human consumption causes **blue baby syndrome.**

NMP's prevent N pollution

Excess N is lost to **air** by volatilization of ammonia or denitrification to N2.

- Emission of N gases causes ozone depletion & acid rain.

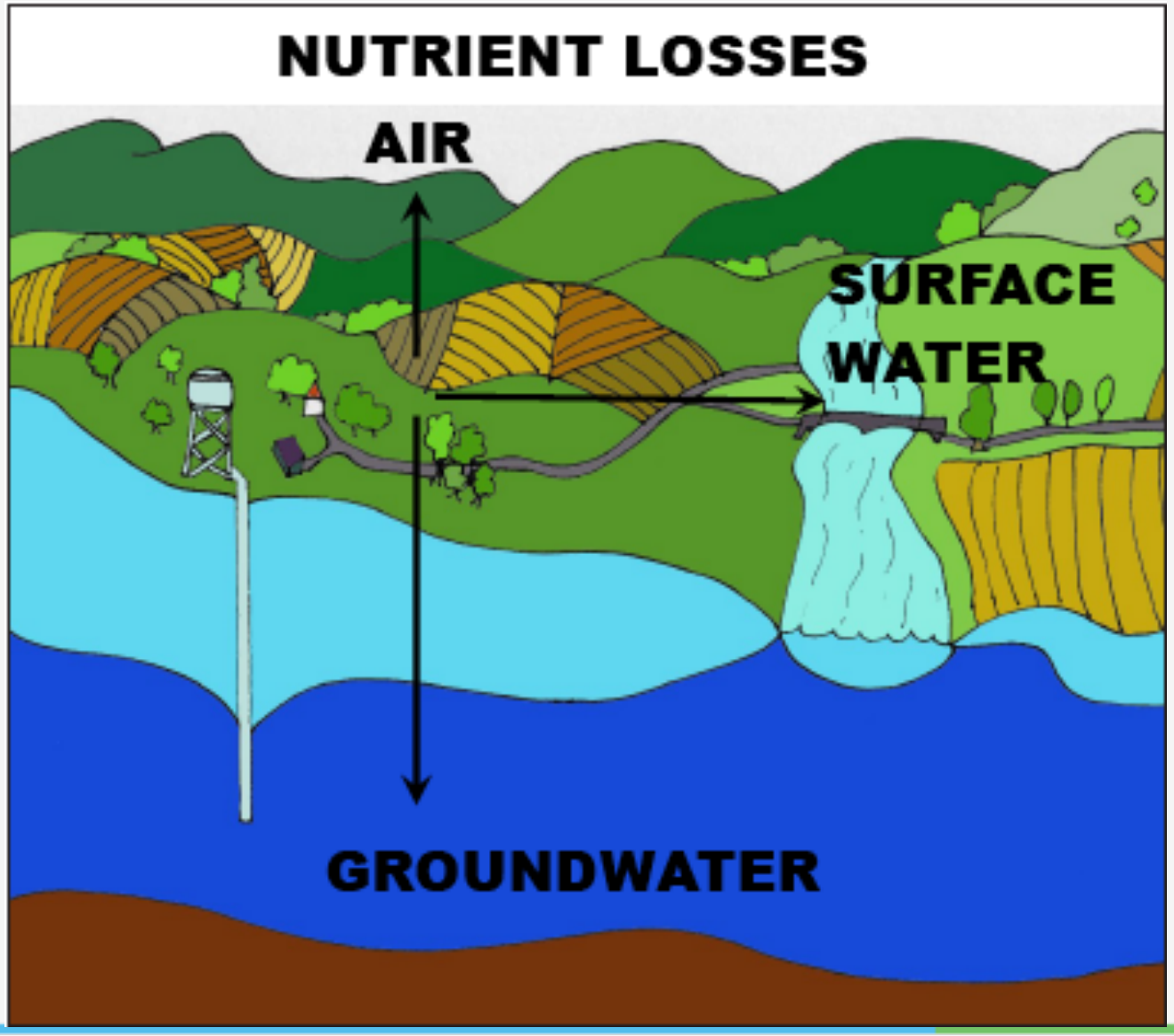
Excess N contaminates **ground and surface water** when nitrates leaching through soil & into groundwater.

- Nitrate in drinking water at > 10 ppm causes human and animal health concerns.
  - Blue baby syndrome: infants can't get enough oxygen into their blood and peripheral tissues.

- When N in surface water reaches **saltwater** the excess nutrient causes **algal blooms**, death of eel-grass nurseries for young fish, and oxygen depletion in the water column. The lack of oxygen creates a 'dead zone' devoid of marine life.
  [N is the more dangerous nutrient in salt water.]

Darby (2009)

NMP's prevent N pollution



Darby (2009)

NMP's prevent P pollution

Excess P contaminates **ground and surface water** when soluble phosphorous leaches into surface water, or when phosphorous bound to soil sediments runs off or erodes into surface water.

- When P in surface water or soil sediment reaches **fresh water** the excess nutrient causes **algal blooms** and oxygen depletion in the water column. The lack of oxygen creates a 'dead zone' devoid of aquatic life. [P is the more dangerous nutrient in fresh water.]

In Vermont, phosphorous pollution of **Lake Champlain** is a serious problem that will take decades to resolve. The EPA may force Vermont to take dramatic and expensive action that will have significant effects of farming and living in the Lake Champlain watershed.

Darby (2009)

Estimating the risks?

Tools used to create nutrient management plans help estimate the risk of nutrient runoff or leaching and pollution of waterways:

- P index
- N leaching index
- RUSLE2
- Locations of wells, waterways and wetlands

In addition to proper nutrient management strategies, using the proper amount of nutrients applied in the right way at the right time, **best management practices (BMPs)** help ensure that nutrients stay out of ground and surface water.

Information about a variety of BMPs and the incentives offered to farmers who implement them is available at:
BMP link

8.7: Phosphorous removal strategies

Phosphorous removal technologies

While the most common technologies involve screening, there are others:

- Primary & secondary sequential screenings for fibers & fines
- Advanced systems not using chemicals
- Advanced systems using chemicals
- Struvite cryrstallization
- Enhanced biological P removal

Primary & secondary (sequential) screening

Removal of fibrous material & fines by primary or sequential screening is nearly an industry standard for AD. Separation uses **screens and screw press augers**, and may use additional mechanical devices like:

- Dewatering augers
- Roller presses
- Vibrating screens
- Automated cleaning systems

Fibrous material has mature markets: bedding, compost base, etc.

There is not yet a mature market for **fines**, but separation of fines and development of a market for them is critical to harvesting and reuse of P.

Sequential screening case study

Double A Dairy in Jerome ID: 12,500 cows with an AD

- Screening system:
  1. 3 primary fibrous solids screens with a slope screen to 2 roller presses
  2. 2 secondary vibrating screens with finer mesh to produce fines
  3. Separate collection & processing areas for fibers vs. fines

Data: 350 yards of wet fiber/day and fines

Fines would be a more valuable product if they were pelleted & dried. This would require more capital & operating investment.

Parameter	Sequential Screening
TS reduction	35 – 40%
Total N reduction	15 – 20%
Total P reduction	12 – 18%
NR capital costs	$35 – 40 / cow
NR operating costs	$5 – 6/cow/year

Andgar (2013)

Sequential screening + advanced systems

Advanced systems added to capture smaller fines are used in combination with (following) sequential screening:

- Rotating screens
- Low-g centrifuge screens
- Decanting centrifuges

Screening + low-g centrifuge case study

Big Sky Dairy, Jerome ID: 3,000 wet cow equivalent dairy with AD

1. Primary screening system
2. Pilot low-g centrifuge

Parameter	Centrifuge only	Screen + centrifuge
TS reduction	30 – 35%	55 – 60%
Total N reduction	10 – 15%	25 – 30%
Total P reduction	40 - 50%	50 – 65%
% moisture	77%	
Cent capital costs	$57 - 136 / cow	
Cent operating costs	$25 – 50/cow/year	

Andgar (2013)

Screening + advanced systems + chemicals

Chemicals are added to cause flocculation of small suspended particles.

Flocculation: reduction of the electrical charge (usually negative), and thus electrostatic repulsion, of small colloidal particles that allows particles to clump together, aggregate, grow and settle

Typical flocculants:

1. **Cationic** (aka coagulant) = positively charged
   - Alum (aluminum sulfate)
   - Ferric chloride
2. **Polymers** = long, branched, high MW molecules that trap particles; may be charged
3. **Binders**, like fibrous solids, that can assist coagulants or polymers by increasing particle size & flocculation

Refinement & optimization of flocculation systems should focus on decreasing inputs and costs.

DVO (2013); Kemira (2011)

…+ harvesting systems

Harvesting systems are typically **mechanical systems** used to separate the flocculated particles from nutrient depleted liquid effluent.

- Settle
- Float & skim
- Dewater

And additional drying and pelletizing may also increase the value of recovered P.

DVO (2013); Kemira (2011)

Screen + chemical + mechanical case study

Bio-Town AD facility, Reynolds IN: 6,000 wet cow equivalent, co-digestion AD

1. Primary screening for fibrous solids
2. Secondary screening for fine solids
3. DAF with organic polymer flocculant, skimming, auger press dewatering

Parameter	Complete system
TS reduction	75 – 80%
TSS reduction	95 – 97%
Total N reduction	50 - 55%
Total P reduction	85 - 95%
NR capital costs	$130 - 150 / cow
NR operating costs	$25 - 30/cow/year

Dosing flocculants

$FeCl_3$ and alum removed 93% & 89% of orthophosphate when the dosed at 90 mg/L, or 0.090 g/L.

40% $FeCl_3$ is 40 g/100 mL, or 400 g/L

If we dose at 50 gallons per day, the concentration of $FeCl_3$ is diluted depending on total feed volume:

Daily feed volume (gallons/day)	Dilution factor	Effective dose (g/L)
10,000	X 200	2.0
12,000	X 240	1.7
16,000	X 320	1.25
16,000	***X 4444.4***	***0.090***

DVO (2013); Zhang & Li (1998)

Simultaneous use of several flocculants

A 2012 study demonstrates that flocculants have optimal pH ranges. Note that CaO (lime) and iron sulfate function well in the same pH range and could be used together. Conversely, alum works in a very different pH range.

Flocculant	Optimal dose (mg/L)	Optimal pH	Phosphate removal (%)
CaO	40	8.5 - 10	90
$Al_2(SO_4)_3$	40	4	85
$Fe_2(SO_4)x$	40	8.5 – 10	80

Lime (CaO) has fallen out of favor because it is harder to store and handle & because it increases the bulk of solids or sludge.

Nassef (2012)

How bioavailable is separated P?

Morse 'P removal & recovery techniques', Sci Total Environ, 212: 69 - 81

Struvite crystallization

Struvite is a hydrated salt precipitate, $MgNH_4PO_4$-$6H_2O$, that co-precipitates N and P. Struvite formation is sensitive to several factors:

- pH
- Supersaturation of Mg, ammonium, phosphate ions
- Presence of calcium impurities (forming $Ca_3(PO_4)_4$ precipitates instead)

Struvite technology has been used to remove up to 80% total P from swine manure.

However, the calcium present in dairy manure has reduced performance of traditional struvite systems to 15% total P.

Modified struvite systems are more effective with dairy manure, allowing 75% removal of total P.

Battistoni (2006); Jeong & Hwang (2005); Le Corre (2007); Bowers & Westerman (2005); Zhang (2010)

Modified struvite case study

Qualco Digester, Monroe WA: 1,400 wet cow equivalent with co-digestion AD

- Pilot scale struvite crystallizer
- Used on post-screening effluent
- High operating costs were due to cost of chemical inputs
- Pelletized product is dry & easily transported

Parameter	struvite	+ screen
Total N reduction	10%	25 – 35%
Total P reduction	75%	85 - 90%
NR capital costs	$75 – 125/cow	
NR operating costs	$80 – 100/cow/year	

Advanced biological P removal

P-accumulating organisms (PAOs) are bacterial species that store P. PAOs are given an advantage by alternating anaerobic & aerobic conditions:

1. Anaerobic:
   - PAOs consume VFAs & reduce them to poly-β-hydroxyalanoates (PHA)
   - PAOs release intracellular P
2. Aerobic:
   - PHAs are oxidized to produce energy
   - P is now taken up by PAOs that use the nutrient to grow, resulting in net uptake of P & accumulation in microbial biomass

This process is complex and affected by:

- Competing bacterial species & processes
- pH
- Temperature
- Organic loading rate
- Availability of **carbon** & macro- & micro-nutrients

Complexity & high cost have discouraged use

Mino (1998); Ahn (2007); Yanosek (2002)

Algae systems

Growth of microalgae on AD effluent consumes and sequesters nutrients into growing algal biomass.

Algae biomass is then harvested for a number of possible uses:

- Algal lipids can be removed and used for biofuel production or dietary supplements;
- Whole algae can be used as AD feedstock; or
- As field amendment.

Challenges:

- Penetration of light into opaque effluent;
- Contamination / competition by other microbes;
- Methods for separating algae from effluent

Parameter	Complete system
TSS reduction	90 – 100%
Total N reduction	80 - 100%
Total P reduction	90 - 100%

As of 2013, more R&D is needed & warranted.

Sialve (2009); Uellendahl & Ahring (2010); Wang (2010); Algevolve (2013)

P removal summary

NR Technology	Performance	Operating cost ($/cow/year)	Capital cost ($/cow)	Scale
Sequential screening	TN 15 – 30% TP 15 – 25%	$5 – 6	$ 32 – 36	commercial
Screening + advanced	TN 24 – 30% TP 50 – 65%	$ 25 - 50	$25 – 50	commercial
Screening + advanced + chemical	TN 45 – 55% TP 75 – 90%	$25 - 75	$25 - 75	commercial
Struvite	TN 30% TP 75%	$90 - 110	$100 - 150	commercial
Biological	TP 42 – 91%	$150 – 170	$275 - 300	pilot

8.8: Nitrogen removal strategies

Nitrogen recovery & recycling

Nitrogen is a macronutrient that is required for vegetative growth of plants.

Creation of **synthetic nitrogen fertilizer** (ammonia) via the Haber reaction requires enormous amounts of fossil fuel and has a large greenhouse gas footprint and is arguably unsustainable.

- 12 kWh/kg N
- 1.4 – 2.6 kg CO_2/kg N

Overuse, or inappropriate use and loss, of nitrogen fertilizer has negative effects, including:

- Eutrophication
- Nitrate leaching
- Greenhouse gas emissions (NOx)
- Air pollution by ammonia particulates

Capture and recycling of organic nitrogen from organic wastes will improve the economics of farming and mitigate environmental impacts.

 Sutton (2009); Wood & Cowie (2004)

N in dairy manure

Diary manure contains significant levels of N:

- 0.6% wet or 5% by dry weight
- 50% is **organic N**
- 50% is soluble **ammonia**

Anaerobic digestion converts 25 – 40% of the organic N to **ammonia**, increasing the bioavailability of N to plants.

- Note that ammonia is also easily lost (volatilized) if not stored or spread properly.

Note that solids separation and collection of fines will harvest some N, mainly as organic N. Solids separation should be considered a pre-requisite to any additional form of N recovery.

Ammonia stripping

Because ammonia is a **gas** at certain temperatures and pH values, this property can be used to remove (or strip) ammonia from liquid effluent.

Stripping methods include:

- Chemical air stripping
- Non-chemical air stripping
- Vacuum stripping
- Steam stripping

- Because AD increases effluent pH and temperature, it facilitates stripping. However, stripping is still **expensive.**
- Older stripping technologies were easily **clogged** be residual solids in effluent, but newer methods have largely resolved that problem.
- Harvested ammonia gas is converted into **crystalline salts** by combination with inorganic or organic acids or rock salts.
- Ammonia recovery is more necessary, and thus more economical, in **poultry** operations than in dairy operations.

Jiang (2013); Lei (2007); Liao (1995); Frear (2011); Zhao (2012)
Speindler (2011); Pedros (2013)

Ammonia stripping case study

Wenning Poultry, Fort Recovery, OH: 1.5 million layer hens with manure AD

- Ammonia is air stripped without chemicals
- Harvested ammonia is reacted with sulfuric acid to produce ammonium sulfate solution
- Remaining effluent is sent through DAF for removal of P-rich solids
- Depleted effluent is mixed with manure for AD

Parameter	AD, NR, DAF
TS reduction	70 – 75%
TSS reduction	93 – 97%
Total N reduction	55 - 65%
Total P reduction	80 - 90%
(NH4)2(SO4)	4 – 5 dry tons/day
NR capital costs	$400 - 500/cow
NR operating costs	$100 - 160/cow/year

 DVO (2013)

Biological conversion to non-reactive N

Several biological methods can convert ammonia N to non-reactive N. These technologies are commercially applied at wastewater treatment plants.

1. Conventional nitrification-denitrification:
   1st aerobic nitrification to nitrite (NO_2^{-1}) & nitrate (NO_3^{-1})
   2nd anaerobic denitrification to N_2 gas
   Two sequential steps are expensive. And the 2nd step requires C that has been removed during AD.

2. Simultaneous nitrification-denitrification (SND) in a single vessel. This is possible only if oxygen levels are strictly controlled.

3. Shortcut biological nitrogen removal (SBNR) ammonia is oxidized to nitrite but not to nitrate; nitrite is then reduced to N_2 gas.

4. Anaerobic ammonium oxidation (Anammox): oxidation of ammonia with nitrite as the electron donor to yield N_2 gas. CO_2 supplies the carbon, and this carbon source works better with AD.

Eekert (2012); Wiesmann (1994); Ahn (2006); Zhu (2008); Vlaeminck (2012)

Biological conversion case study

Watson Dairy, Trenton FL: 800 wet cow equivalents

- Dairy manure → solids separation → integrated nitrification / denitrification
- AD omitted because the carbon is needed for N_2 recovery
- Effluent is clarified by flocculation & additional P removal

Parameter	AD, NR, DAF
Total N reduction	88%
Total P reduction	67%
NR capital costs	$438 - 563/cow
NR operating costs	$80 - 104/cow/year

FPPC (2007)

Summary of N removal technologies

Technology	Performance	Operational ($/cow/year)	Capital ($/cow)	Scale
Ammonia stripping	TN 65 – 85% TP 85 – 90%	$100 - 190	$450 - 650	commercial
Conversion to non-reactive N	TN 80 – 90% TP 65 – 95%	$80 - 180	$425 - 575	pilot

8.9: Salt removal & clean water strategies

Recovery of clean water by removal of salt

Ideally, effluent could be separated into macronutrients and clean water. Removal of water would decrease the cost and effort required to store, transport and spread nutrients and would decrease use of fresh water.

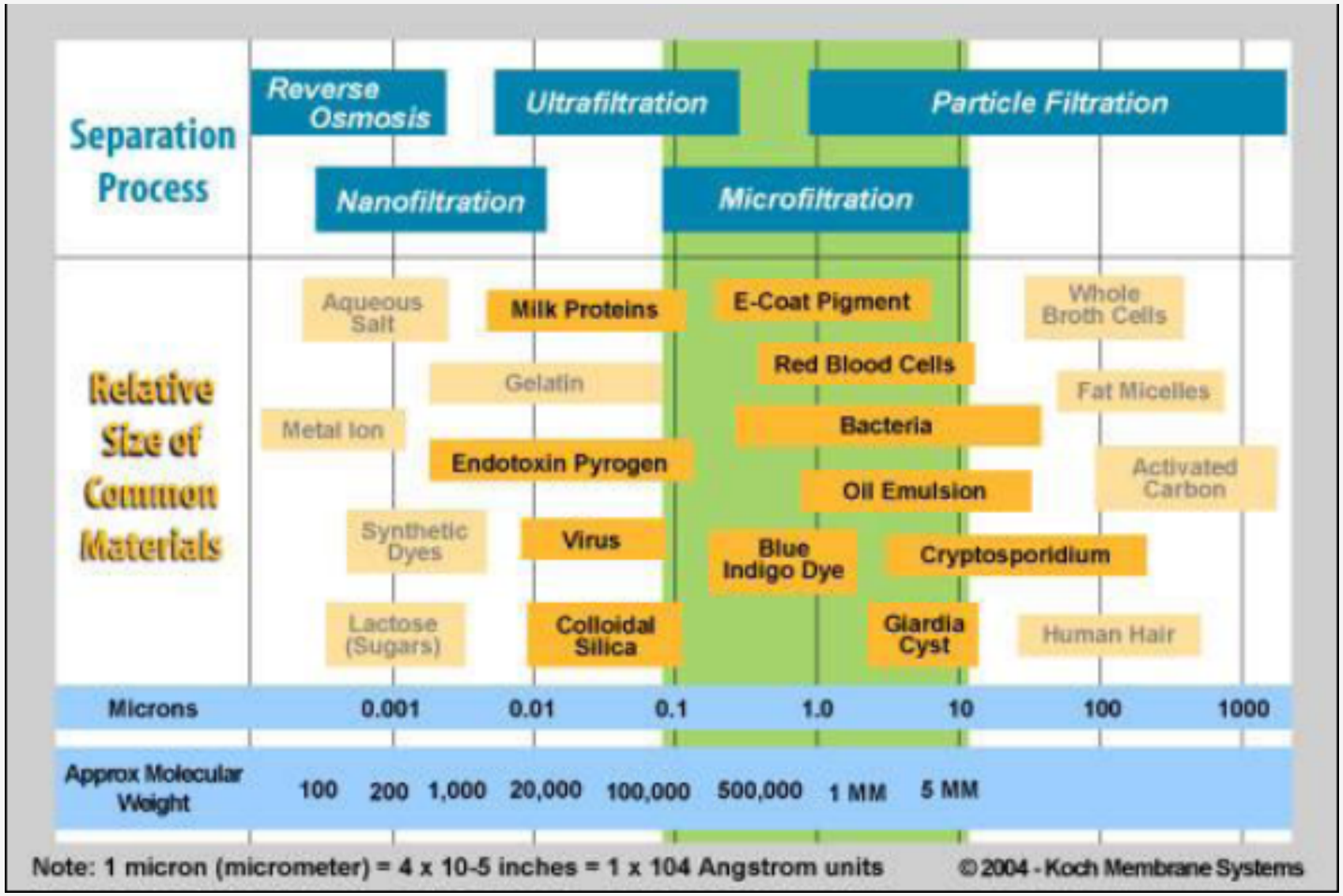
Membranes are used to separate water from salts:

1. **Microfiltration** uses pore sizes from 0.1 to 1.0 micron and low pressure to separate water from large solids.
2. **Ultrafiltration** uses a smaller pore size – 0.001 to 0.1 micron – and removes polymers, and high molecular weight molecules & substances.
   Both filtrations can only remove soluble molecules if they are absorbed to activated carbon or coagulated with alum or iron salts.
3. **Reverse osmosis** uses pore sizes of 0.0001 microns and produces pure water.

Sequential recovery is needed to prevent large particles or molecules from clogging RO filters.

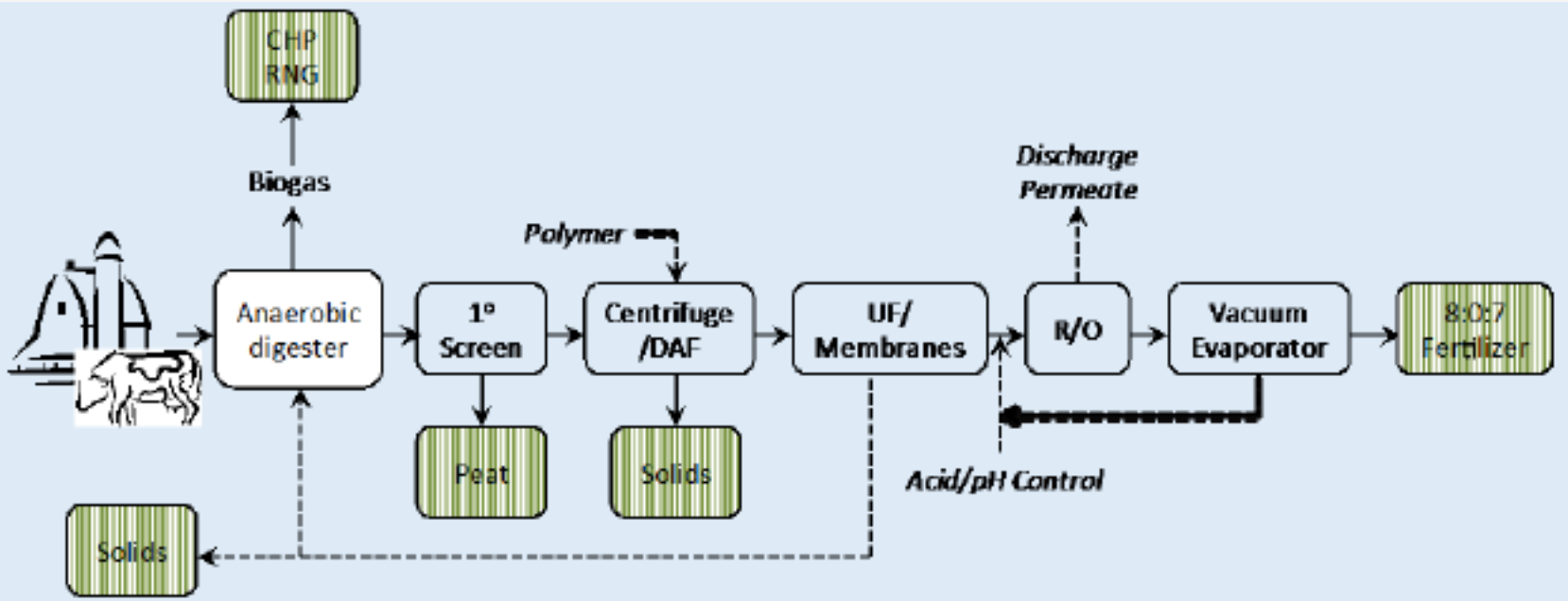
Churchouse (1999); Peter-Varbanets (2009); Mulder (2000)

Filtration technologies



Filtration case study

Poultry pilot



Technology	Performance	Operational ($/cow/year)	Capital ($/cow)	Scale
System + membrane filtration	TN ~100% TP ~100% TK ~100%	$900 - 1000	$ High!	pilot

Halpern (2013)

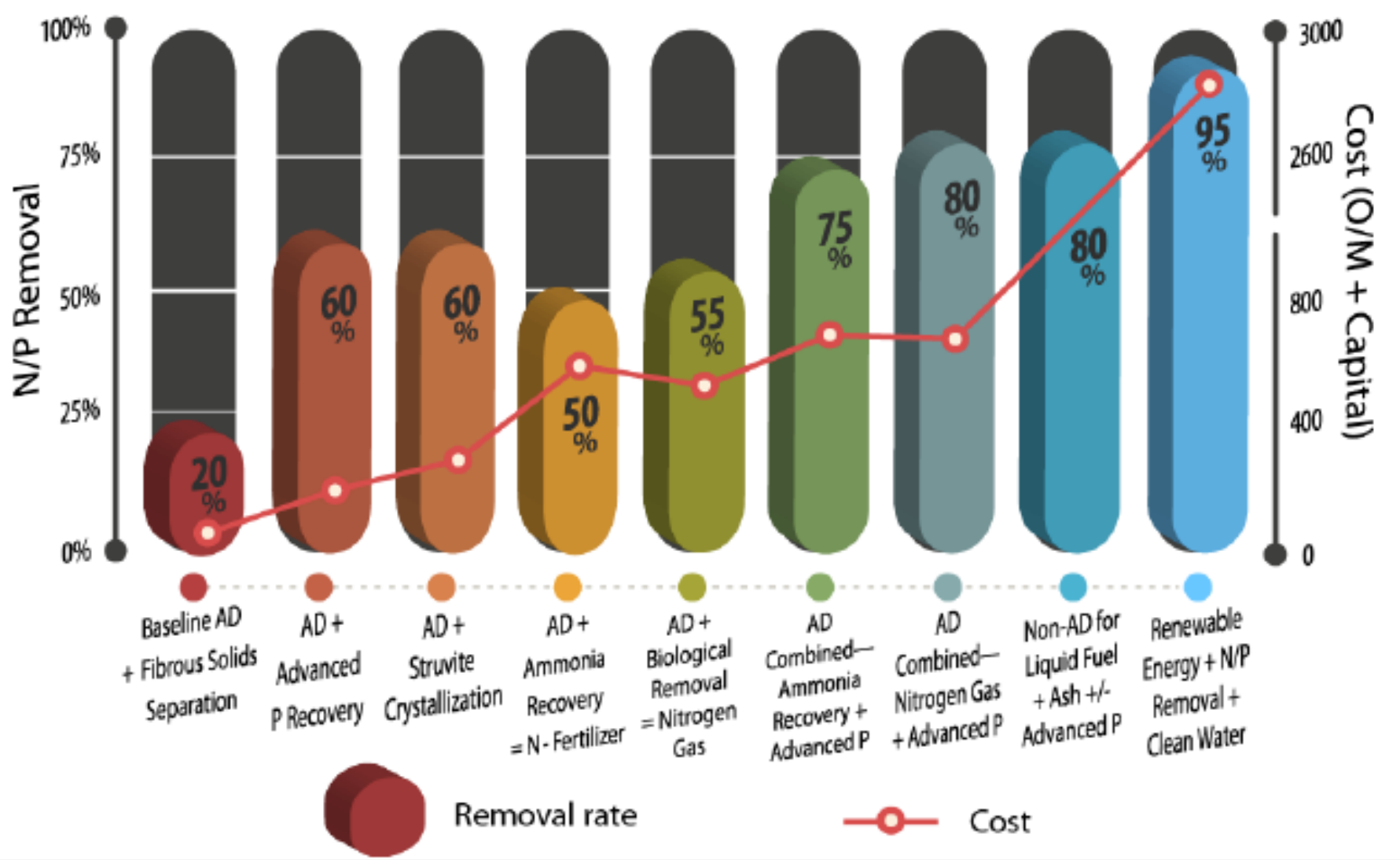
Energy costs are so high

… that use of filtration technologies turns a renewable energy project into a clean water project.

This is laudable… but different.

Halpern (2013)

Overall comparison of separation strategies



Ma (2013)

Sources & resources (1)

This curriculum is a modification of the wonderful:

- eXtension Course 3: AD, University of Wisconsin

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