THE THREE PATHWAYS FOR THE REMOVAL OF AMMONIA-NITROGEN IN AQUACULTURE SYSTEMS

James M. Ebeling, Ph.D.
Research Engineer
Aquaculture Systems Technologies, LLC

Michael B. Timmons, Ph.D.
Professor
Dept. of Bio. & Environ. Eng.
Cornell University

Introduction

$C_{inorganic}$ / N Ratio

Ammonia-nitrogen

$C_{organic}$ / N Ratio

Photoautotrophic

(green-water systems)

NH_4^+-N → $C_{106}H_{263}O_{110}N_{16}P$

Algae

Autotrophic

(fixed-cell bioreactors)

NH_4^+-N → NO_2^--N

Ammonia Oxidizing Bacteria

NO_2^--N → NO_3^--N

Nitrite Oxidizing Bacteria

Heterotrophic

(zero-exchange systems)

NH_4^+-N → $C_5H_7O_2N$

Bacteria

“New Paradigm” → ????

??? Understanding of the ‘Removal System’

- Photoautotrophic
- Autotrophic
- Heterotrophic
- Some Combination!

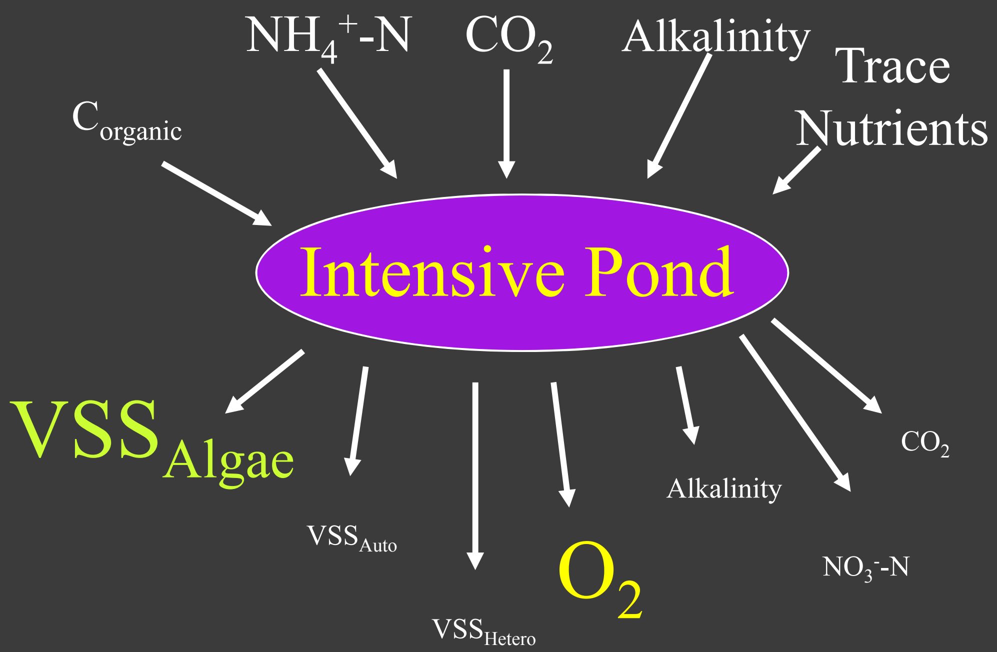
Impact on Water Quality!!!!

Management Strategies!

Nitrogen Removal Pathways

- Photoautotrophic
- Autotrophic
- Heterotrophic
- *Other Mysterious Ways*

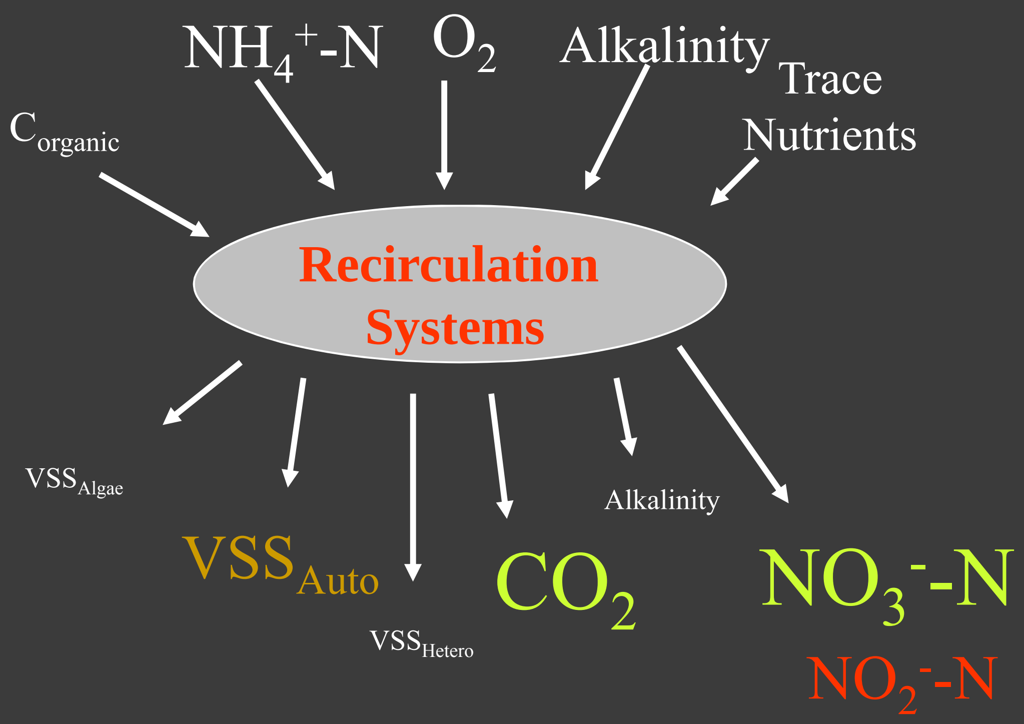
Nitrogen Removal Pathways



- Photoautotrophic
  - Autotrophic
  - Heterotrophic
  - Other Mysterious Ways

Algae Based Systems

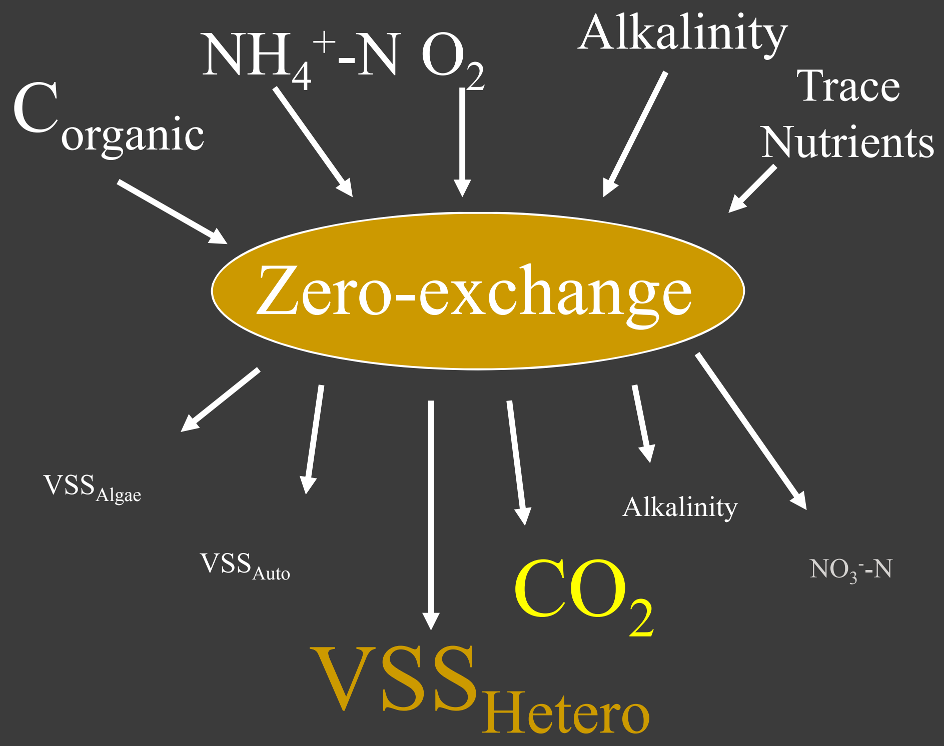
Nitrogen Removal Pathways



- Photoautotrophic
- Autotrophic
- Heterotrophic
- Denitrification

Fixed-film Bioreactors

Nitrogen Removal Pathways



- Photoautotrophic
- Autotrophic
- Heterotrophic
- Denitrification

Suspended Growth Systems

Photoautotrophic (algal based systems)

Biosynthesis of saltwater algae:

Nitrate as nitrogen source

$$16\ NO_3^- + 124\ CO_2 + 140\ H_2O + HPO_4^{2-} \rightarrow$$

$$C_{106}H_{263}O_{110}N_{16}P + 138\ O_2 + 18\ HCO_3^-$$

Ammonia as nitrogen source

$$16\ NH_4^+ + 92\ CO_2 + 92\ H_2O + 14\ HCO_3^- + HPO_4^{2-} \rightarrow$$

$$C_{106}H_{263}O_{110}N_{16}P + 106\ O_2$$

Photoautotrophic (algal based systems)

Consumables	Stoichiometry	Consumes (g)	C organic (g)	C inorganic (g)	N (g)
NH_4^+-N		1.0	-----	-----	1.0
Carbon Dioxide	18.07 g CO_2/ g N	18.07	-----	4.93	-----
Alkalinity	3.13 g Alk/ g N	3.13	-----	0.75	-----

Products	Stoichiometry	Yields (g)	C organic (g)	C inorganic (g)	N (g)
VSS_{Algae}	15.85 g VSS_A / g N	15.85	5.67	-----	1.0
Oxygen	15.14 g O_2/ g N	15.14	-----	-----	-----

Autotrophic - Nitrification

Biosynthesis of Autotrophic bacteria:

$$NH_4^+ + 1.83\ O_2 + 1.97\ HCO_3^- \rightarrow$$

$$0.024\ C_5H_7O_2N + 0.976\ NO_3^- + 2.9\ H_2O + 1.86\ CO_2$$

The major factors affecting the rate of nitrification include:

- ammonia-nitrogen and nitrite-nitrogen concentration
- carbon/nitrogen ratio
- dissolved oxygen
- pH
- temperature
- alkalinity
- salinity

Autotrophic - Nitrification

Consumables	Stoichiometry	Consumes (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
NH_4^+-N		1.0	-----	-----	1.0
Alkalinity	7.05 g Alk/ g N	7.05	-----	1.69	-----
Oxygen	4.18 g O_2/ g N	4.18	-----	-----	-----

Products	Stoichiometry	Yields (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
VSS_A	0.20 g VSS_A / g N	0.20	0.11	-----	0.024
NO_3^--N	0.976 g NO_3^--N /g N	0.976	-----	-----	0.976
CO_2	5.85 g CO_2/ g N	5.85	-----	1.58	-----

Heterotrophic Bacteria

Biosynthesis of Heterotrophic bacteria:

$$NH_4^+ + 1.18\ C_6H_{12}O_6 + HCO_3^- + 2.06\ O_2 \rightarrow$$

$$C_5H_7O_2N + 6.06\ H_2O + 3.07\ CO_2$$

The major factors affecting the rate of nitrification include:

- ammonia-nitrogen
- carbon/nitrogen ratio
- dissolved oxygen
- pH
- temperature
- alkalinity
- salinity

Heterotrophic Bacteria

Consumables	Stoichiometry	Consumes (g)	C organic (g)	C inorganic (g)	N (g)
NH_4^+-N		1.0	-----	-----	1.0
$C_6H_{12}O_6$	15.17 g Carbs/ g N	15.17	6.07	-----	-----
Alkalinity	3.57 g Alk/ g N	3.57	-----	0.86	-----
Oxygen	4.71 g O_2/ g N	4.71	-----	-----	-----

Products	Stoichiometry	Yield (g)	C organic (g)	C inorganic (g)	N (g)
VSS_H	8.07 g VSS_H / g N	8.07	4.29	-----	1.0
CO_2	9.65 g CO_2/ g N	9.65	-----	2.63	-----

Impact of C/N Ratio

↓ C/N Ratio ↑

Autotrophic		Heterotrophic
$C_{labile}/N \sim 0$	$C_{labile}/N \sim 2.2$	$C_{labile}/N \sim 6.2$
$C_{organic}/N \sim$ small	$C/N \sim 8\text{-}10$	$C/N \sim 12\text{-}16$
inorganic carbon as alkalinity	organic carbon from the feed	organic carbon from the feed plus supplemental carbohydrates
100 % Autotrophic	(109 g $C_{organic}$ /kg feed) @ 35% protein	100% Heterotrophic
(Recirculation System with excellent solids removal)	56 % Heterotrophic 44 % Autotrophic	

Autotrophic ⟷ Heterotrophic

Autotrophic (Intensive Recirculation System)

Autotrophic System

Conversion of 1 kg of feed @ 35% protein

$$32.2 \text{ g N} * 0.20 \text{ g VSS/ g N}$$

$$= 6.44 \text{ g VSS}_{autotrophic}$$

0.124 gN/gVSS_A → 0.80 g N_{VSS} + $31.4 \text{ g NO}_3\text{-N}$

0.531 gC/gVSS_A → 3.42 g C_{VSS} + 51.3 g CO_2

Autotrophic (Intensive Recirculation System)

Consumables	Stoichiometry	Consumes (g)	C organic (g)	C inorganic (g)	N (g)
NH_4^+-N		32.2	-----	-----	32.2
Alkalinity	7.05 g Alk/ g N	227	-----	54.7	-----
Oxygen	4.18 g O_2/ g N	135	-----	-----	-----

Products	Stoichiometry	Yields (g)	C organic (g)	C inorganic (g)	N (g)
VSS_A	0.20 g VSS_A / g N	6.44	3.4	-----	0.8
NO_3^--N	0.976 g NO_3^--N /g N	31.4	-----	-----	31.4
CO_2	5.85 g CO_2/ g N	188	-----	51.3	-----

54.7g C_{Alk} / 32.2 g N $\rightarrow$ C/N ratio of 1.6 and TOC is very, very small

Biofloc System (?) (no Carbon Supplementation)

Heterotrophic and Autotrophic Components

Heterotrophic Component: Organic Carbon from Feed

$$1\ kg_{feed} * 0.36\ kg\ BOD/kg\ feed\ * 0.40\ kg\ VSS/\ kg\ BOD =$$

$$= 144\ g\ VSS_{heterotrophic}$$

$0.124\ gN/gVSS_H$ → $17.9\ g\ N_{VSS}$

$0.531\ gC/gVSS_H$ → $76.5\ g\ C_{VSS}$

$+ 47.1\ g\ C_{CO2} = 123.6\ g$

C

→ $109\ g\ C_{feed}$ and $15.4\ g\ C_{Alkalinity}$

Assume that the heterotrophic bacteria out compete the autotrophic bacteria.

Biofloc System (?) (no Carbon Supplementation)

Heterotrophic and Autotrophic Components

Autotrophic Component: Inorganic Carbon Alkalinity

Excess Ammonia-nitrogen:

32.2 g NH_3-N - 17.9 g N_{VSS} = 14.3 g N_A

14.3 g N * 0.20 g VSS/ g N

= 2.86 g $VSS_{autotrophic}$

0.124 gN/$gVSS_A$ → 0.35 g N_{VSS} + 14 g NO_3-N

0.531 gC/$gVSS_A$ → 1.52 g C_{VSS} + 24.3 g C_{Alk}

Biofloc System (?) (no Carbon Supplementation)

Heterotrophic and Autotrophic Components

Heterotrophic Bacteria	Stoichiometry	Consumes (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
NH_4^+-N	0.56 * N_T	17.9	-----	-----	17.9
$C_6H_{12}O_{6\ feed}$	15.17 g Carbs/ g N	272	109	-----	-----
Alkalinity	3.57 g Alk/ g N	63.9	-----	15.4	-----

Autotrophic Bacteria	Stoichiometry	Consumes (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
NH_4^+-N	0.44 * N_T	14.3	-----	-----	14.3
Alkalinity	7.05 g Alk/ g N	101	-----	24.3	-----

Conversion of 1 kg of feed @ 35% protein

Biofloc System (?) (no Carbon Supplementation)

Heterotrophic and Autotrophic Components

Heterotrophic Bacteria

	Stoichiometry	Yields (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
VSS_H	8.07 g VSS_H / g N	144	76.5	-----	17.9
CO_2	9.65 g CO_2/ g N	173	-----	47.1	-----

Autotrophic Bacteria

	Stoichiometry	Yields (g)	$C_{organic}$ (g)	$C_{inorganic}$ (g)	N (g)
VSS_A	0.20 g VSS_A / g N	2.86	3.45	-----	0.35
NO_3^--N	0.976 g NO_3-N/g N	31.7	-----	-----	13.9
CO_2	5.85 g CO_2/ g N	83.4	-----	22.8	-----

Conversion of 1 kg of feed @ 35% protein

Biofloc System (?) (no Carbon Supplementation)
Heterotrophic and Autotrophic Components

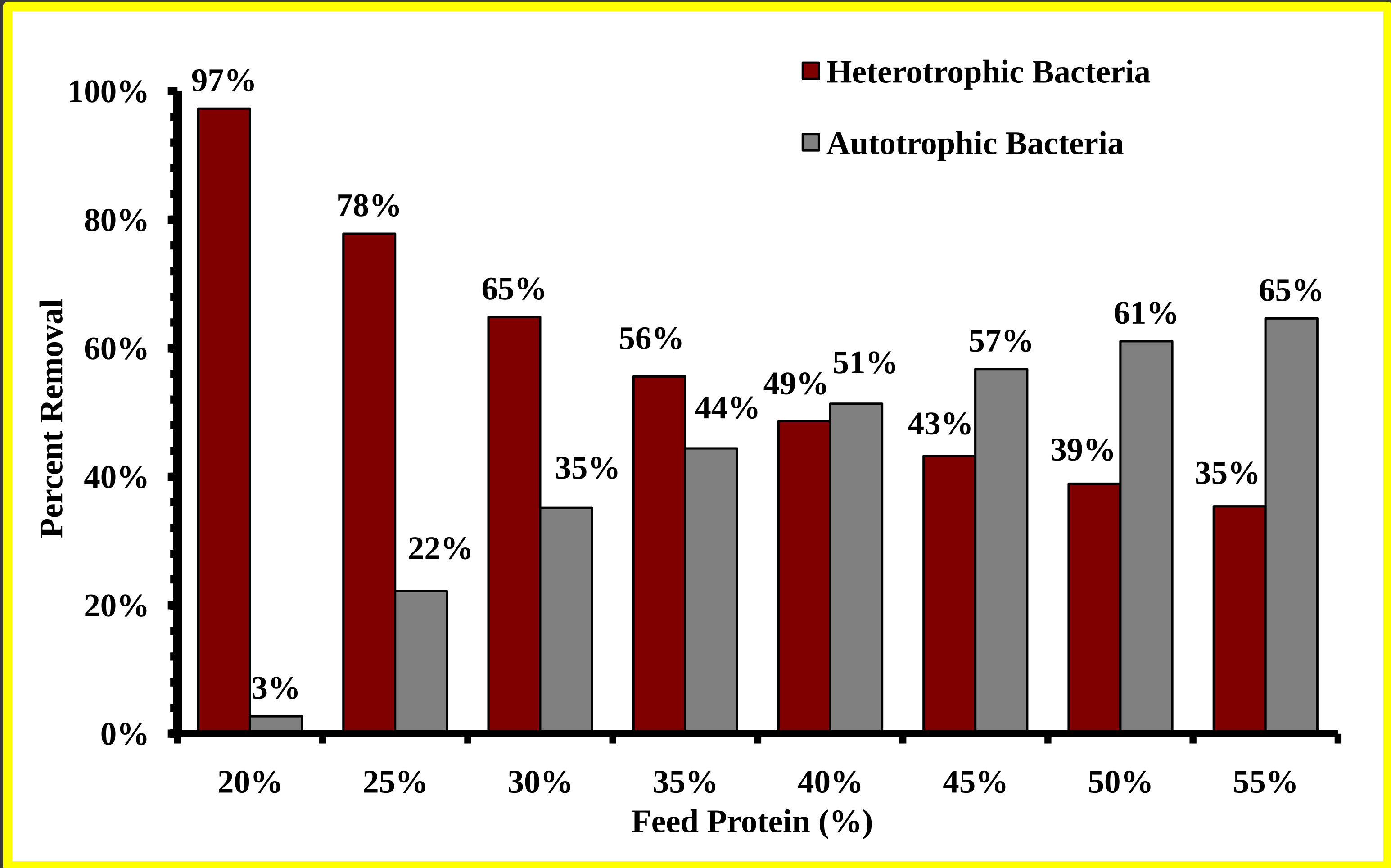
	Consumes	C organic (g)	C inorganic (g)	N (g)
NH_4^+-N	32.2 g N	-----	-----	32.2
$C_6H_{12}O_6$	272 g Carbs (feed)	109	-----	-----
Alkalinity	165 g Alk	-----	40	-----

	Yields	C organic (g)	C inorganic (g)	N (g)
VSS	147 g VSS	80	-----	18.2
NO_3^--N	31.7 g NO_3-N	-----	-----	13.9
CO_2	256 g CO_2	-----	70	-----

Conversion of 1 kg of feed @ 35% protein

Biofloc System (?) (no Carbon Supplementation)

Heterotrophic and Autotrophic Components



Percent removal of ammonia-nitrogen by Heterotrophic or Autotrophic Process as a function of % Protein

Biofloc System

Carbon Supplement

Excess Ammonia-nitrogen:

$32.2g\ NH_3\text{-}N - 17.9\ g\ N_{VSS} = 14.3g\ N_A$

$14.3\ g\ N * 8.07\ g\ VSS / g\ N$

$= 115\ g\ VSS_{heterotrophic}$

$0.124\ gN/gVSS_H$ → $14.3\ g\ N_{VSS}$

$0.531\ gC/gVSS_H$ → $61.1\ g\ C_{VSS}$

$+ 37.6\ g\ C_{CO2} = 98.7\ g\ C$

→ $86.4\ g\ C_s$

→ $12.3\ g\ C_{Alkalinity}$

Carbohydrate is 40% Carbon ⇒ 216 g carbs

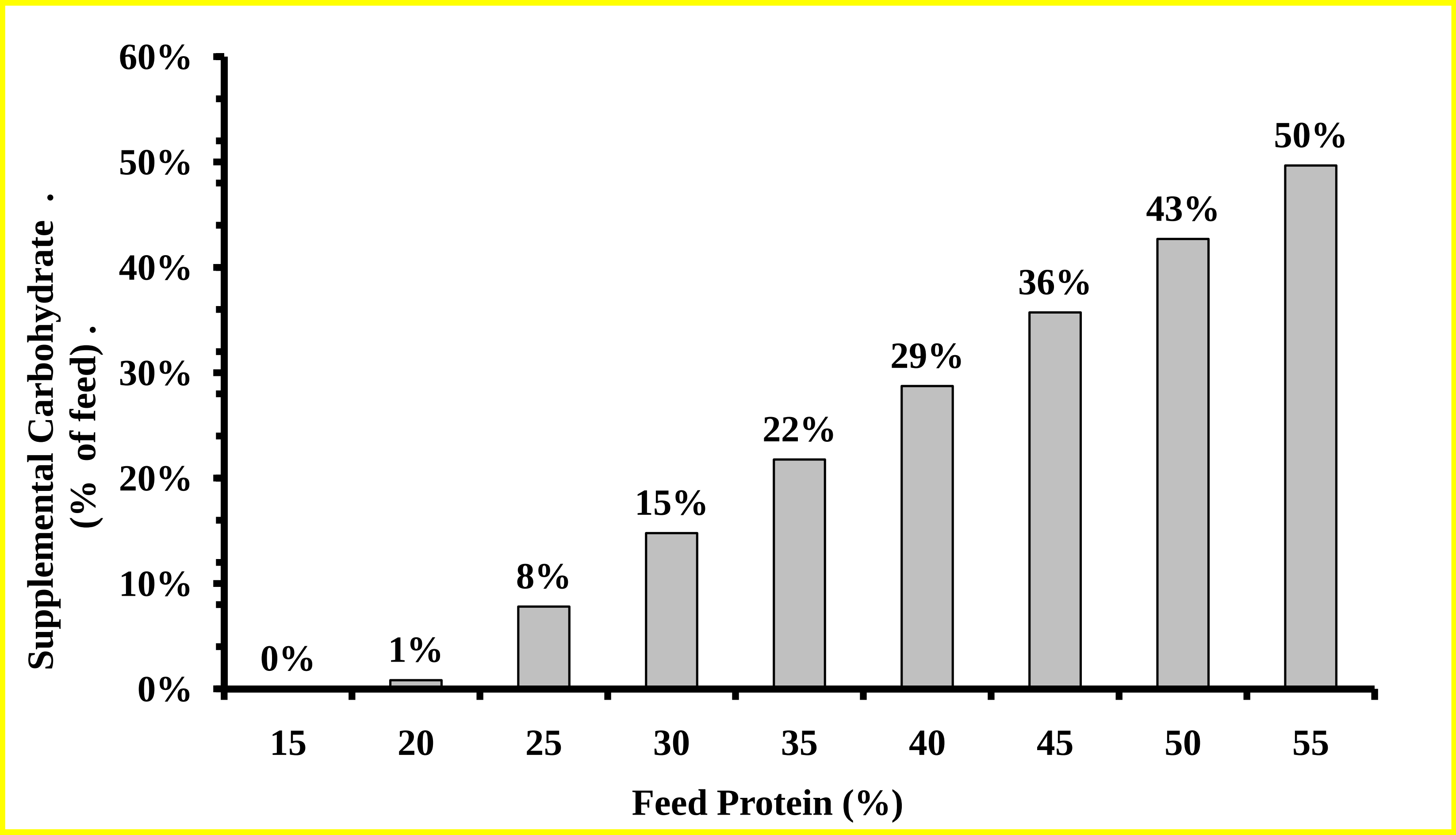
Biofloc System (Carbon Supplementation)

Consumables	Stoichiometry	Consumes (g)	C organic (g)	C inorganic (g)	N (g)
NH_4^+-N		32.2	-----	-----	32.2
$C_6H_{12}O_6$	15.17 g Carbs/ g N	488	196	-----	-----
Alkalinity	3.57 g Alk/ g N	115	-----	27.7	-----
Oxygen	4.71 g O_2/ g N	152	-----	-----	-----

Products	Stoichiometry	Yield (g)	C organic (g)	C inorganic (g)	N (g)
VSS_H	8.07 g VSS_H / g N	260	138	-----	32.2
CO_2	9.65 g CO_2/ g N	311	-----	85	-----

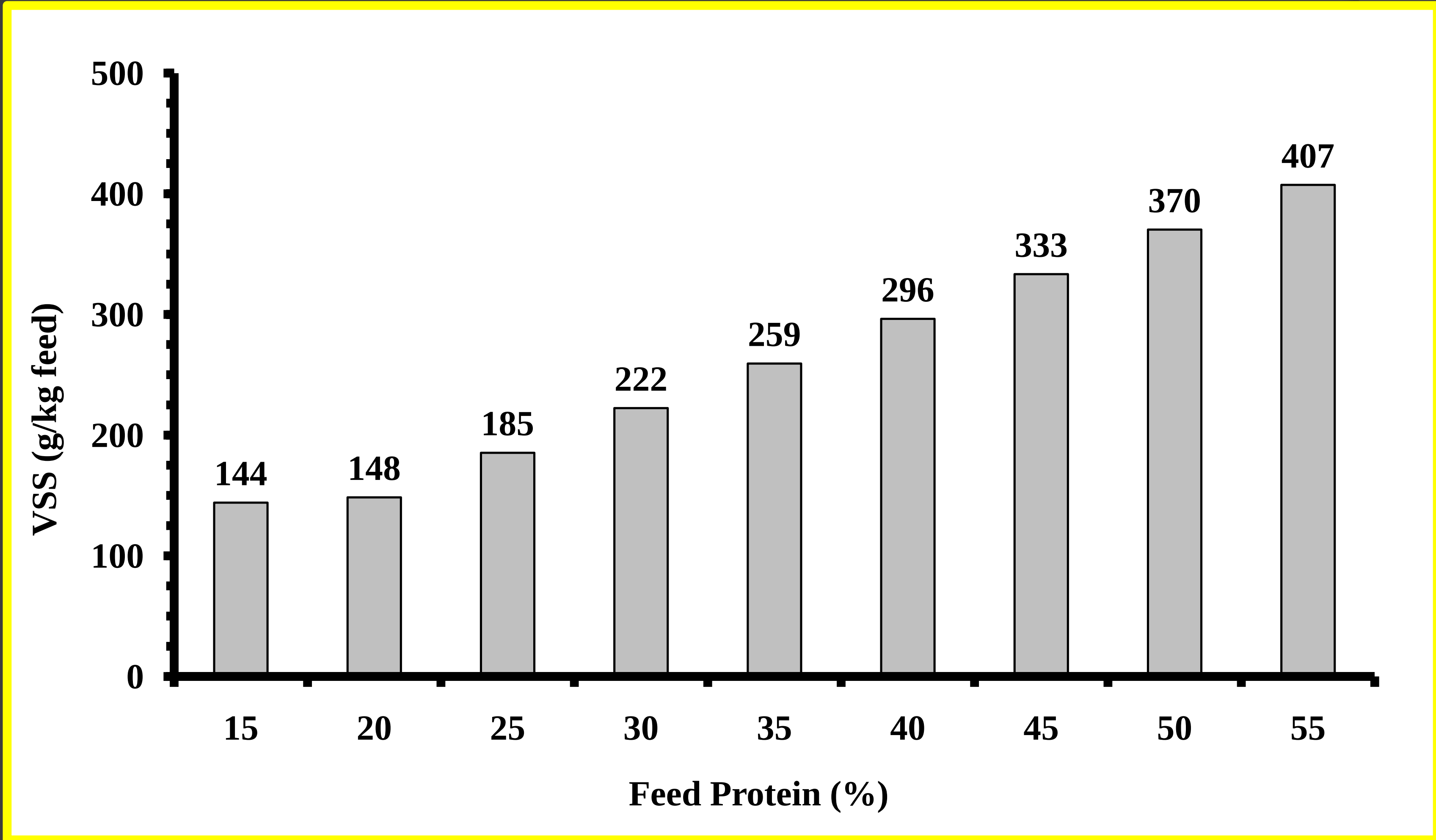
Conversion of 1 kg of feed @ 35% protein

Biofloc System (Carbon Supplementation)



Supplemental Carbohydrate as percentage of feed rate
for heterotrophic metabolism of ammonia-nitrogen to microbial biomass

Biofloc System (Carbon Supplementation)



VSS production as percentage of feed rate
for heterotrophic metabolism of ammonia-nitrogen to microbial biomass

Conclusions

"Engineering Sustainability"

Organic Carbon + Nitrogen → Bacterial Biomass

Questions?