The Messy Details of Going from Excrement to Entrée

(aka 'Going from Poop to Plate')

St. Louis Space Frontier Gateway to Space 2020

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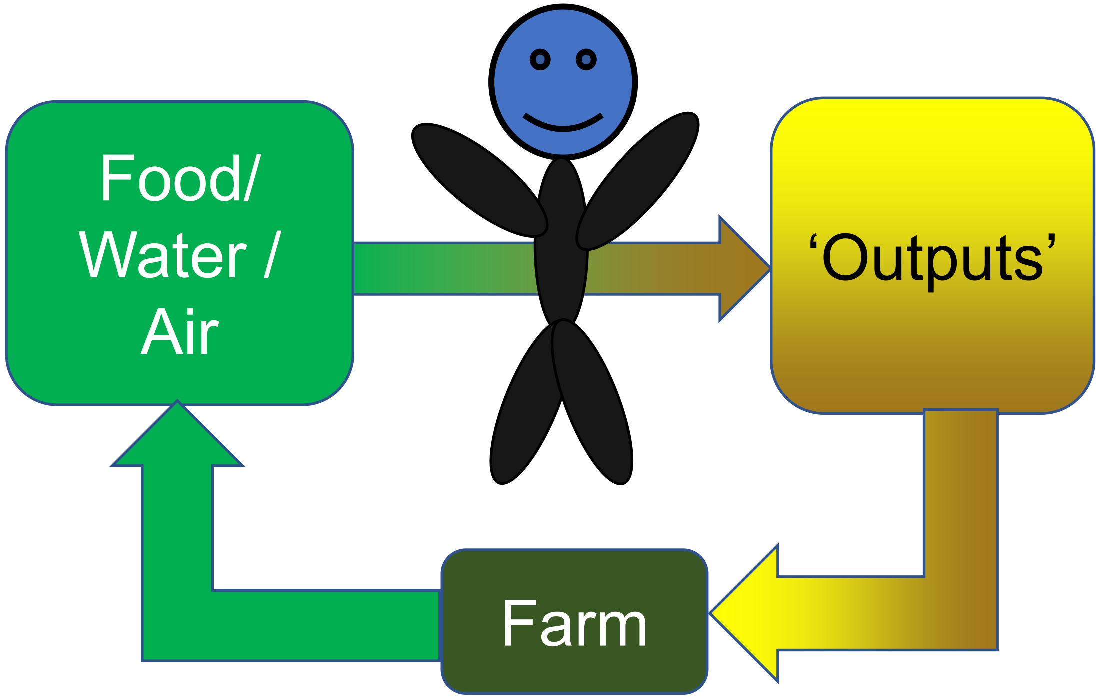
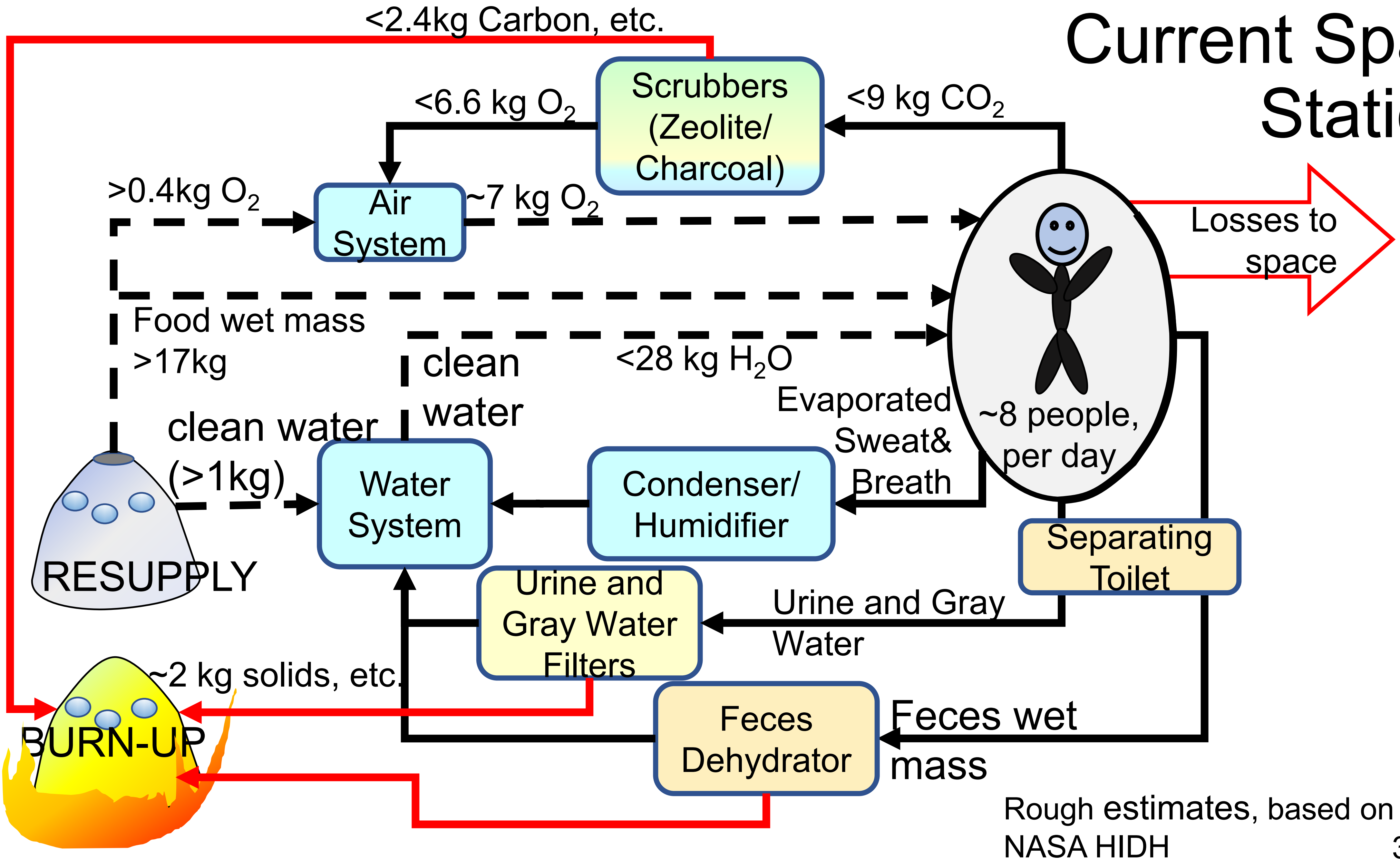
http://www.spacefarms.info

Overview

- Current State: Near Term
- Assumptions
- Method: Element Balances
- Human Model, Menu, Inputs
- Biochemistry of Excrement and Modeled Loads
- Treatment and Tanks
- Urine and Plants



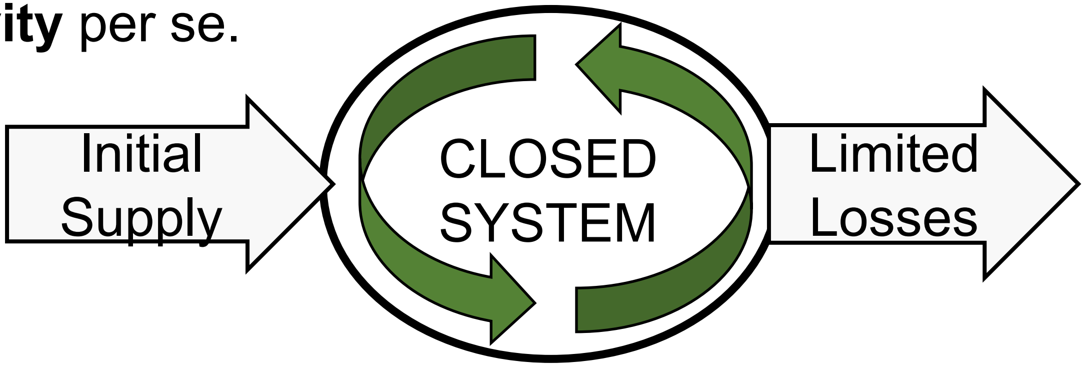
Current Space Stations



Rough estimates, based on NASA HIDH

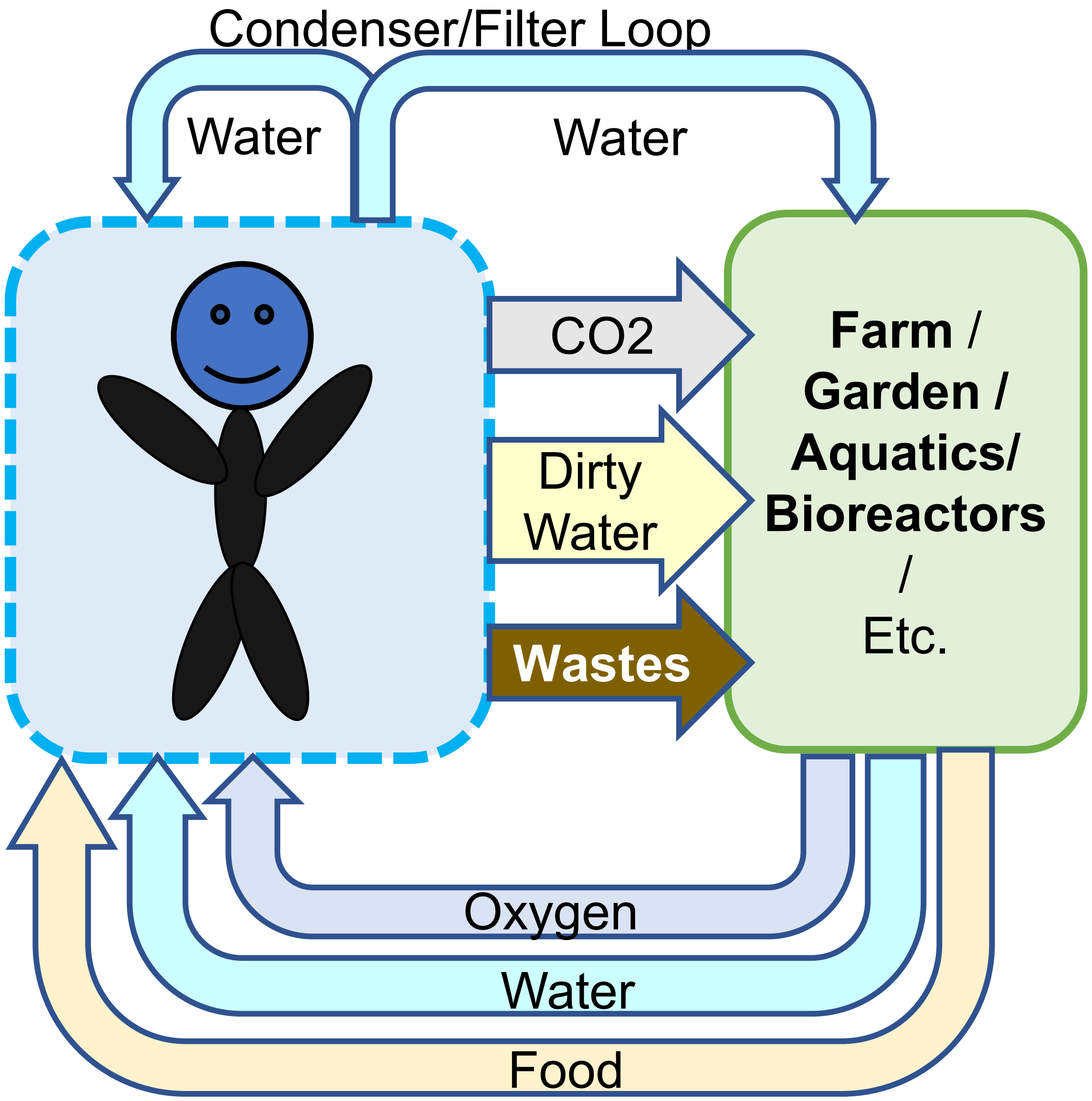
Assumptions

- Treat Farm as a **black box**
- Guess a meal structure for active population 22-50 years old, mixed gender, averaged out to **3,000 calories**
  - Assume a **high protein, high fiber** diet on average, and **one workout per day**.
  - Assume people are **NOT gaining weight**
  - **All dietary fiber ends up in Feces**
- NASA modeled **Oxygen, Carbon Dioxide**
- Mostly **current technologies**
- **Moon, Mars**, and Earth gravities, **not microgravity** per se.
  - Assume **calcium excess in urine**
- **Try for Closed System…**

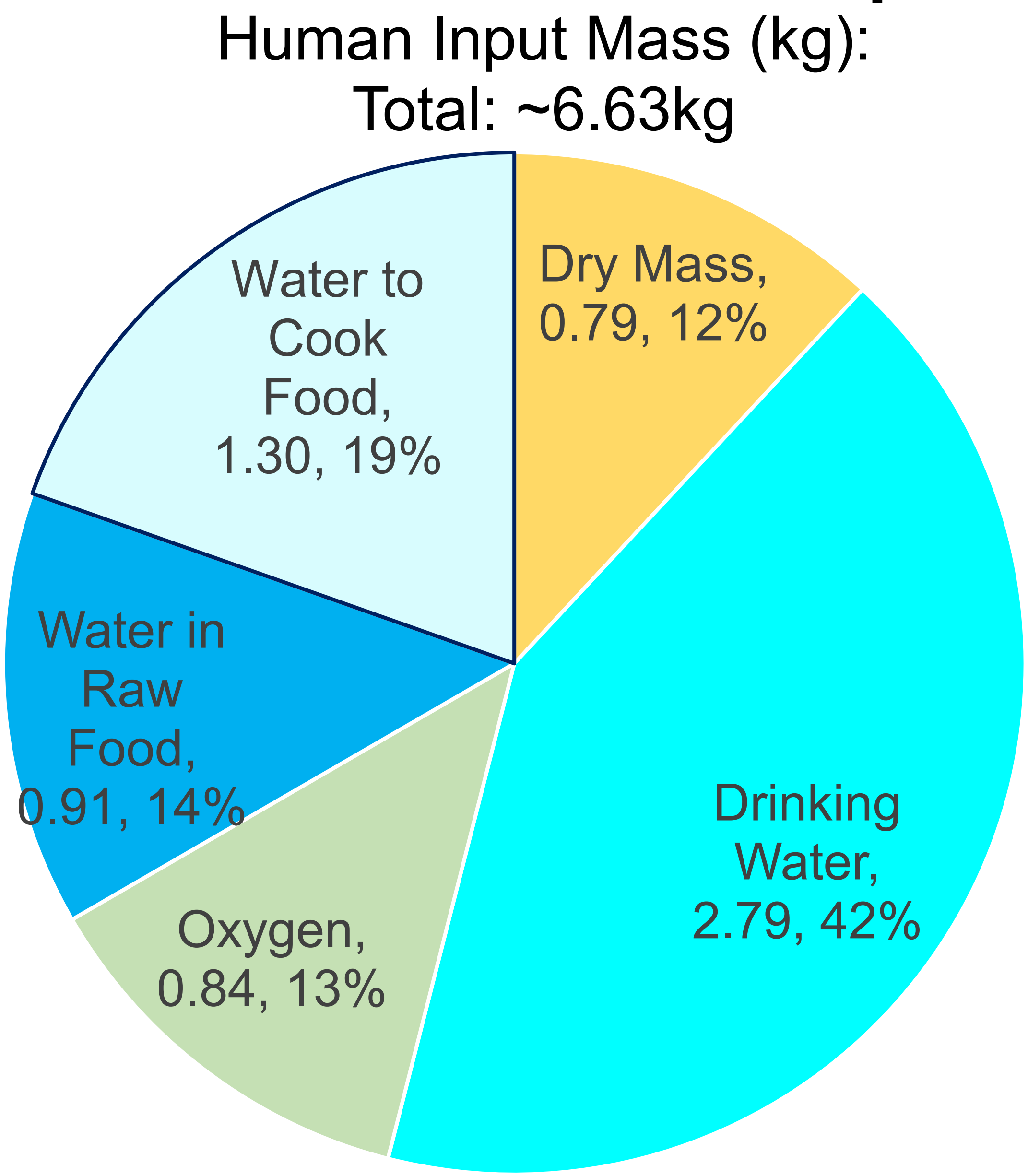


Method and Closed Loop

- Inputs to people are outputs from farm
- Inputs to farm are outputs to people
- FARM= BLACK BOX
- **Method: Balance elements** (i.e. C,H,O,N and FDA nutrient elements + Cl)



Human Model: Example Menu (pp/day)

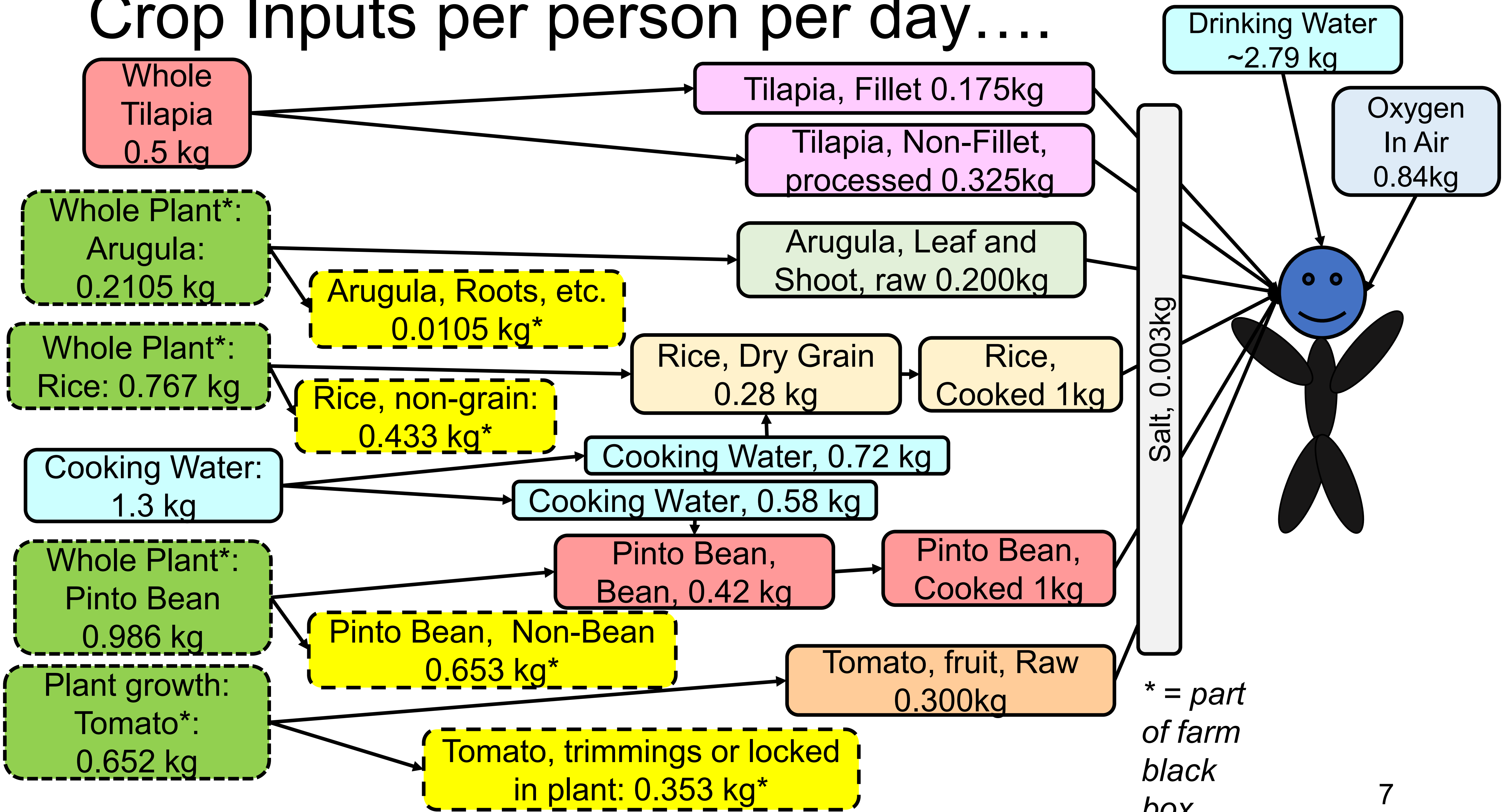


High protein diet for active 20-55-year-old humans. Diet balances key nutrients.

Food	Grams Wet Mass	kcal
Tilapia, raw (whole)	500	480
Pinto Beans, cooked	1,000	1,430
Rice, cooked	1,000	1,010
Arugula, raw	200	50
Tomatoes, raw	300	48
Salt	3	0
TOTAL	**3,003**	**3,018**

Menu Note: Fish non-fillet parts are good to make into stock, fish meal, and sauces.

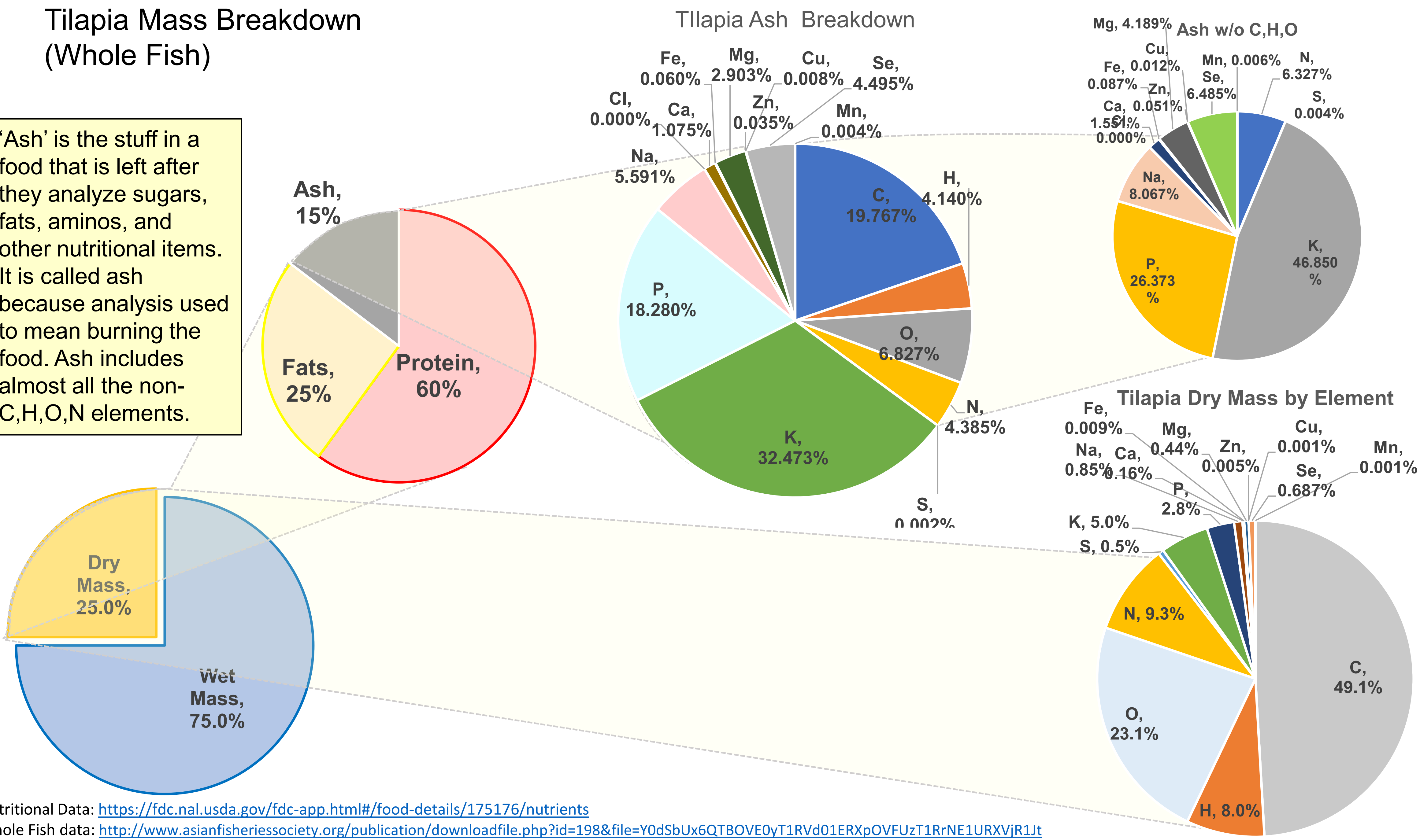
Crop Inputs per person per day….



** = part of farm black box*

Tilapia Mass Breakdown (Whole Fish)

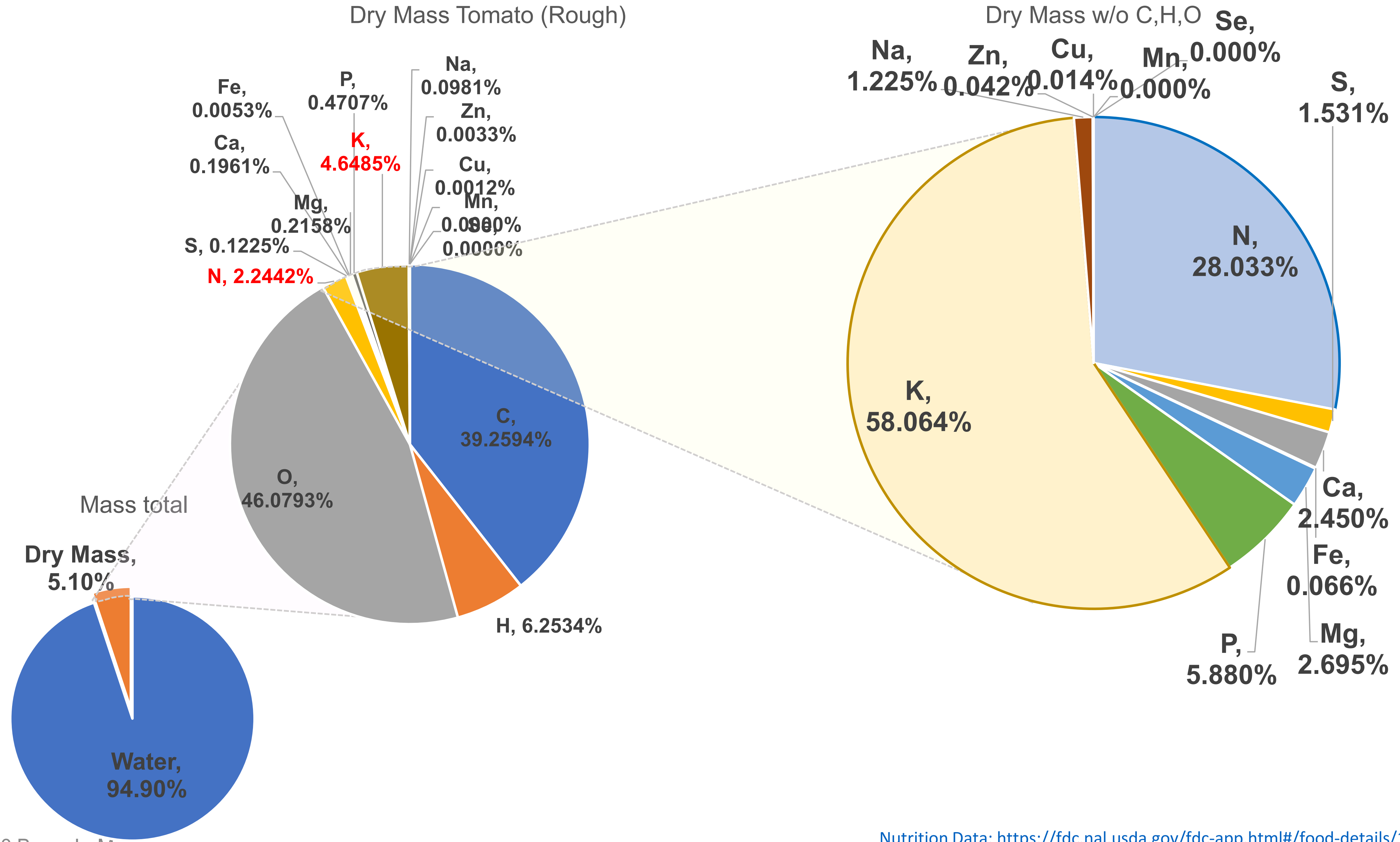
'Ash' is the stuff in a food that is left after they analyze sugars, fats, aminos, and other nutritional items. It is called ash because analysis used to mean burning the food. Ash includes almost all the non-C,H,O,N elements.



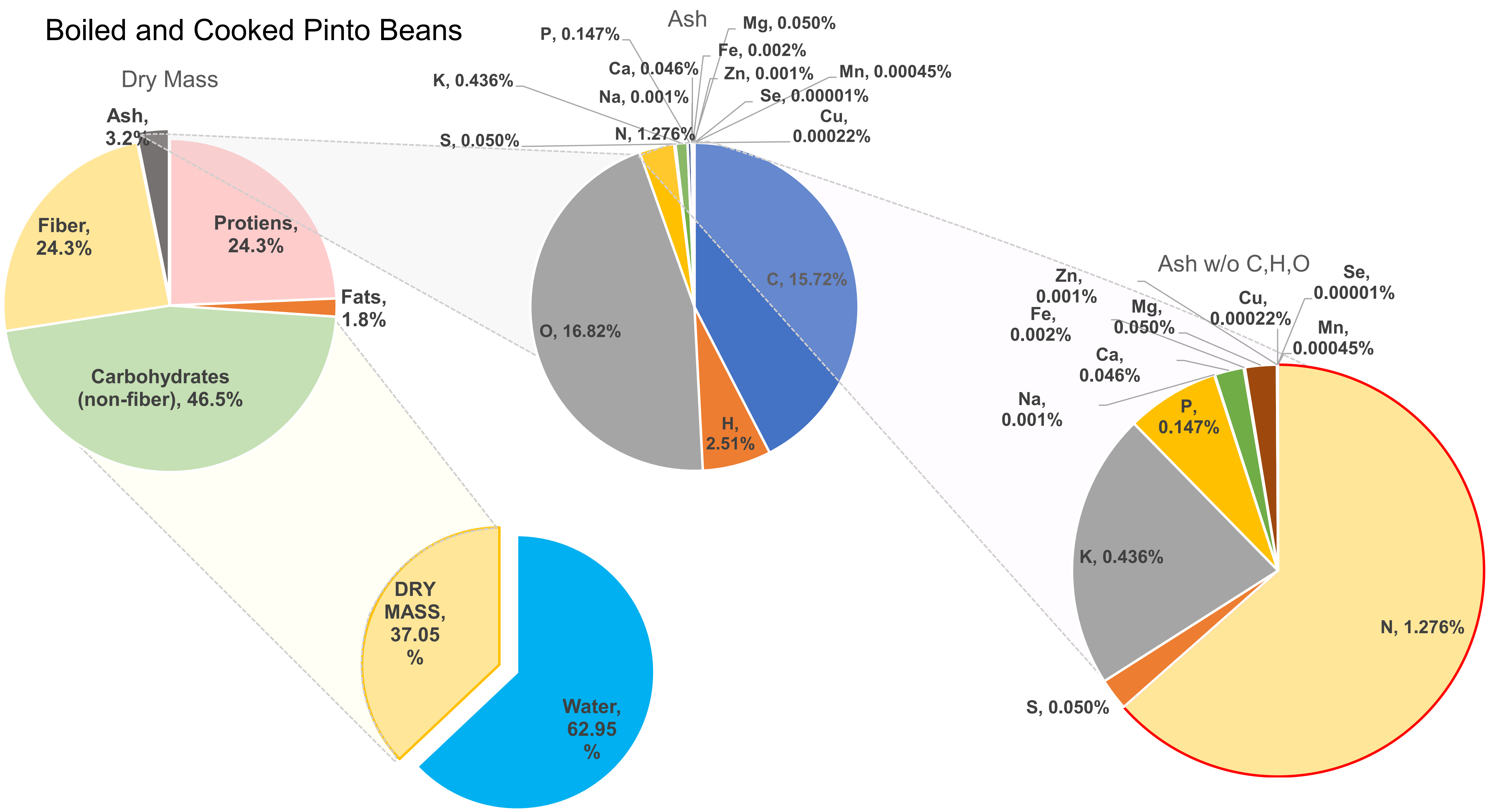
Nutritional Data: https://fdc.nal.usda.gov/fdc-app.html#/food-details/175176/nutrients

Whole Fish data: http://www.asianfisheriessociety.org/publication/downloadfile.php?id=198&file=Y0dSbUx6QTBOVE0yT1RVd01ERXpOVFUzT1RrNE1URXVjR1Jt

Tomato Plant Mass Breakdown

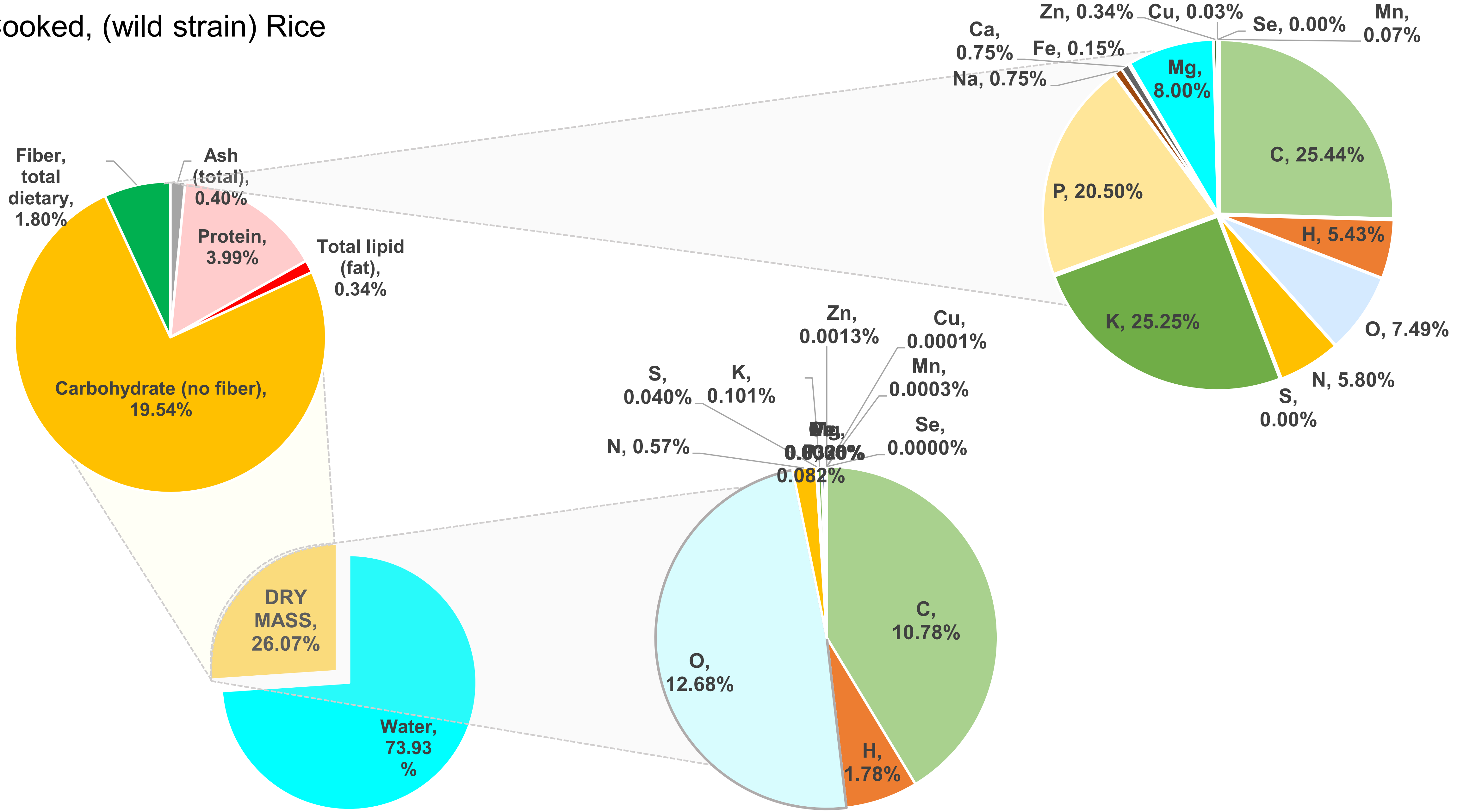


Nutrition Data: https://fdc.nal.usda.gov/fdc-app.html#/food-details/170502/nutrients



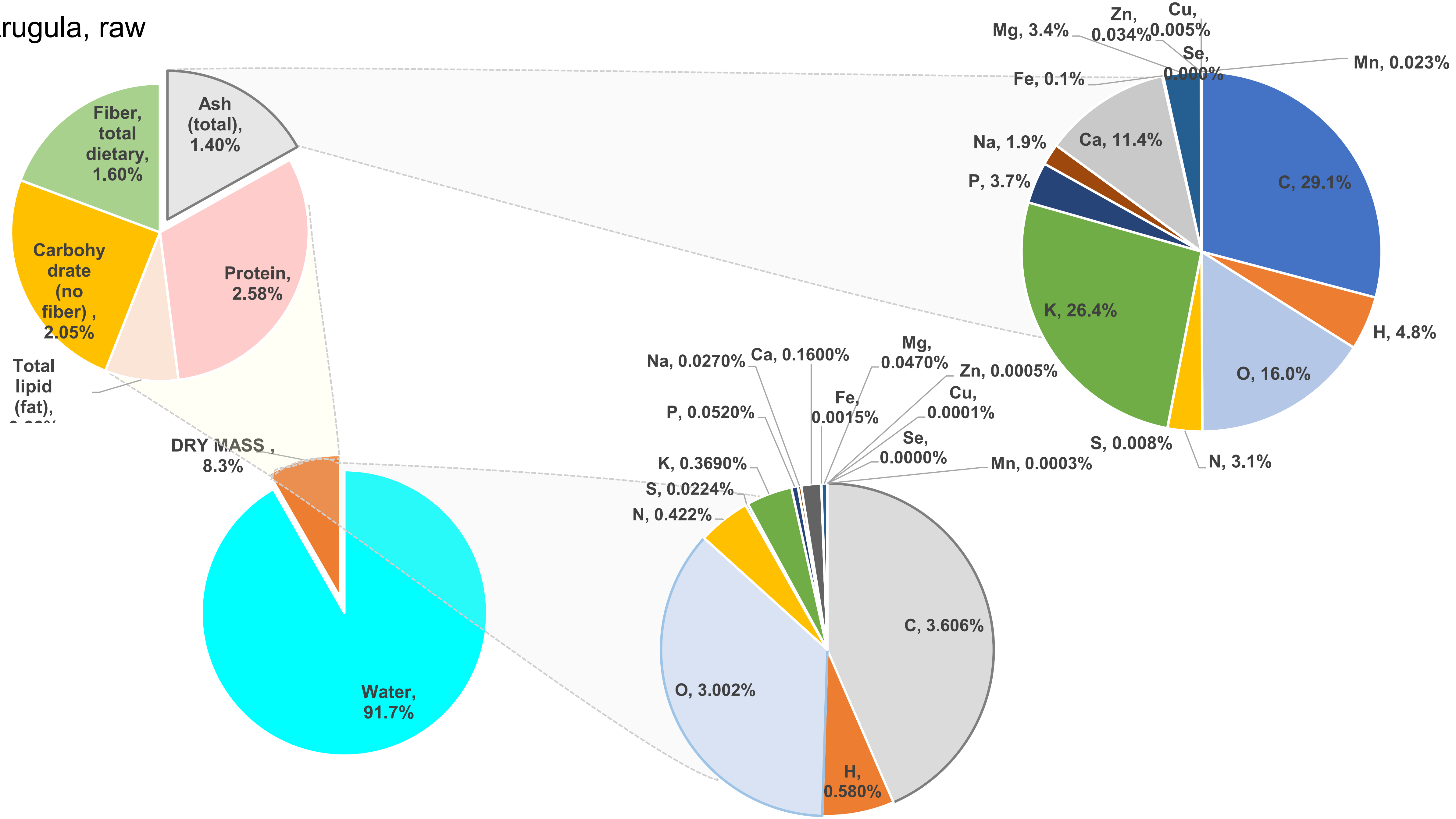
Nutritional Data: https://fdc.nal.usda.gov/fdc-app.html#/food-details/175200/nutrients

Cooked, (wild strain) Rice



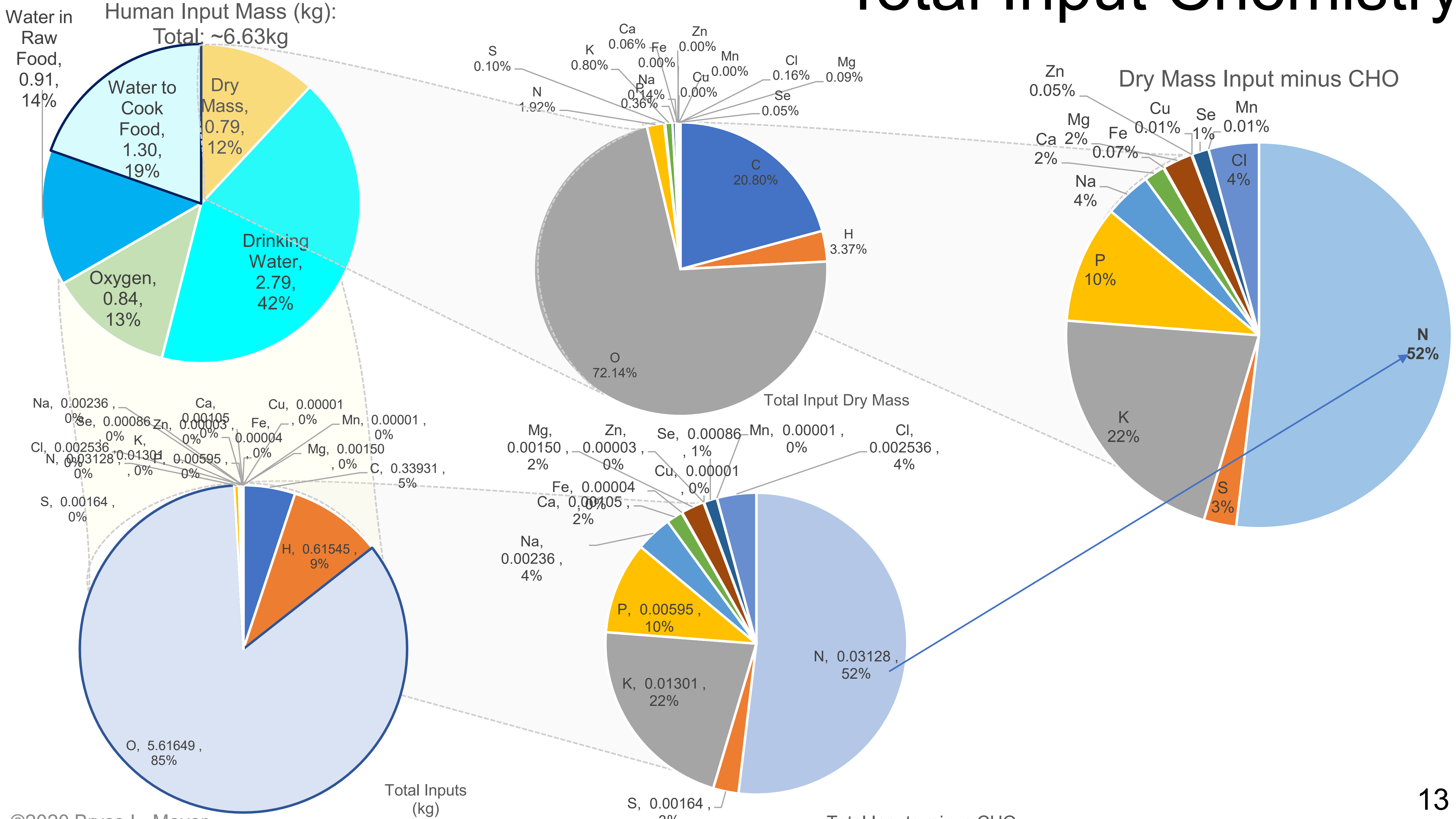
Nutrition data from : https://fdc.nal.usda.gov/fdc-app.html#/food-details/168897/nutrients

Arugula, raw



Nutrition Data from: https://fdc.nal.usda.gov/fdc-app.html#/food-details/169387/nutrients

Total Input Chemistry



Core Biochemistry Reactions

Reaction	Summary Reaction Equation	Why?
Photosynthesis	$6CO_2 + 6H_2O$ + light → $C_6H_{12}O_6 + 6O_2$	How plants grow and feed us.
Aerobic Digestion	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$	How we get energy!
Anerobic Digestion	$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$	Sugar breakdown w/o oxygen.
Ammonia to Urea	$NH_3 + CO_2 \rightarrow CH_4N_2O$	Protein → Ammonia
Cellulose Hydrolysis	$C_6H_{10}O_5 + H_2O$ + enzymes → $C_6H_{12}O_6$ $C_6H_{10}O_5 + H_2O$ + enzymes + $6O_2 \rightarrow 6CO_2 + 6H_2O$	Ways bacteria and some algae use cellulose
Cellulose Burning	$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O$	Incinerators or wildfires

Simple Sugars	$C_6H_{12}O_6$	**Cellulose (fiber)**	$C_6H_{10}O_5$
Methane	CH_4	**Carbon Dioxide**	CO_2
Water	H_2O	**Oxygen Gas**	O_2
Ammonia	NH_3	**Urea**	CH_4N_2O

Biochemistry

- People, animals, fungi, and many bacteria use this core reaction:
  - **Aerobic Metabolism: $C_6H_{12}O_6$ + $6O_2$ → $6CO_2$ + $6H_2O$**
  - In words: **Sugars** + **Oxygen** release cellular energy, **Carbon Dioxide + Water** (Same as burning, but slower!).
- Plants, Algae, and Cyanobacteria work in the reverse, using light energy: Photosynthesis: **$6CO_2$ + $6H_2O$→ $C_6H_{12}O_6$ + $6O_2$**
  - Plants also make **Cellulose**:
    - **$C_6H_{10}O_5$** which a water away from a sugar.….
    - VERY TRICKY TO BREAK DOWN, aka ‘fiber’.

Biochemistry: Cellulose is Tricky

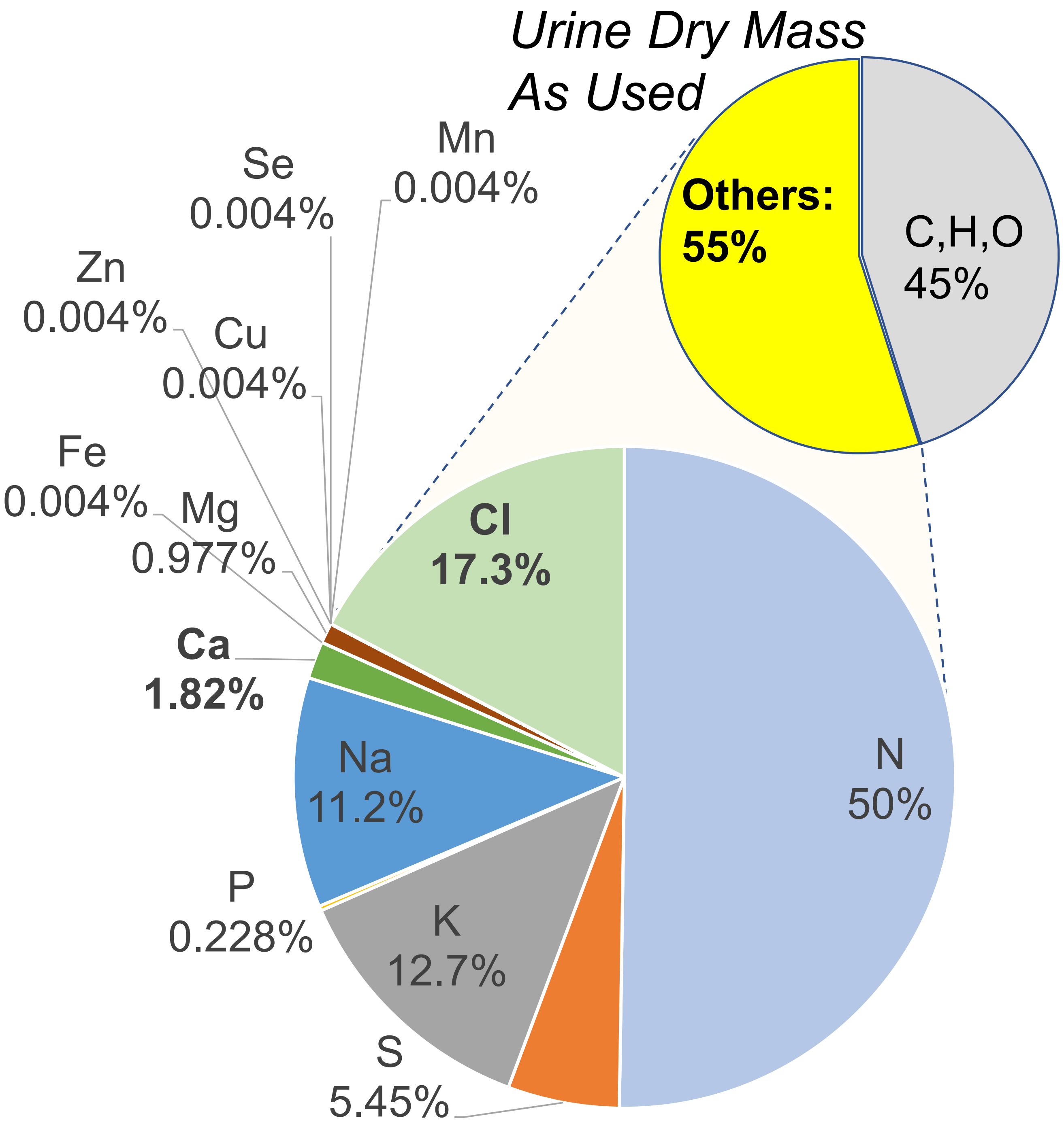
- **Cellulose poses a problem:**
  - Special enzymes, bacteria, or heat used to aerobically break down fiber to get carbon dioxide and water.
  - **Cellulose + Oxygen + enzymes → Carbon Dioxide and Water**
  - **Usually ends up a sludge in most waste processing on Earth**
  - Even cows, termites, fungi (all using bacteria) only partly break down cellulose
  - In nature: **Wildfire (quick) or Bacteria (slow)** in compost heaps or soil do the work
- **In a closed cycle with plants, carbon ends up stuck in cellulose unless broken down!**

Biochemistry: Where does the smell come from?

- **Anerobic Digestion:** Sugars are broken to **Methane (CH_4)** and Carbon Dioxide(CO_2)
  - Methane is a fuel source for energy (fuel cells, burners) and rockets…. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
- Note: Other pathways happen, some use protein breakdown to make **Hydrogen Sulfide: H_2S**
    - **Smells like rotten eggs, broken down from some Amino Acids**
- Protein + Water → Sugars and **Ammonia (NH_3)**
  - In Animals with Kidneys: $NH_3 + CO_2 \rightarrow$ **CH_4N_2O (Urea)**
  - Breakdown (Soil, Ponds, Laundry): Urea → $NH_3 + CO_2$
  - **Plants use Ammonia** to make Amino Acids which can become Proteins

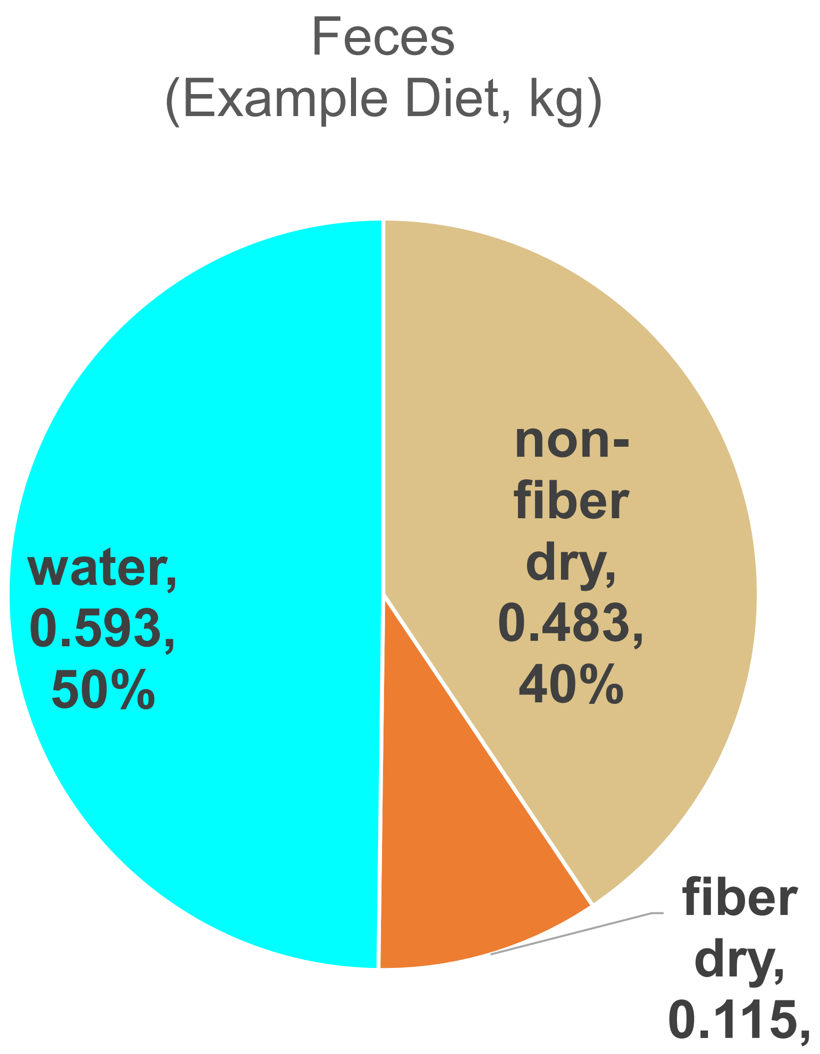
Urine in General…

- Urine is composed of concentrates from what you ate, minus what comes out as feces or sweat.
  - ~0.8% to 3.7% concentration by mass total. 49% Salts (33% = NaCl, K_2SO_4, KCl).
  - In lower gravity, **Calcium salts increase** in concentration
- Assume **~2 kg/day/pp** due to healthy water intake, **2.0%** concentration
- For comparison, seawater is **2.7%** to **3.5%** solutes by mass, almost all salts (i.e. double inorganic salts, subtract urea)

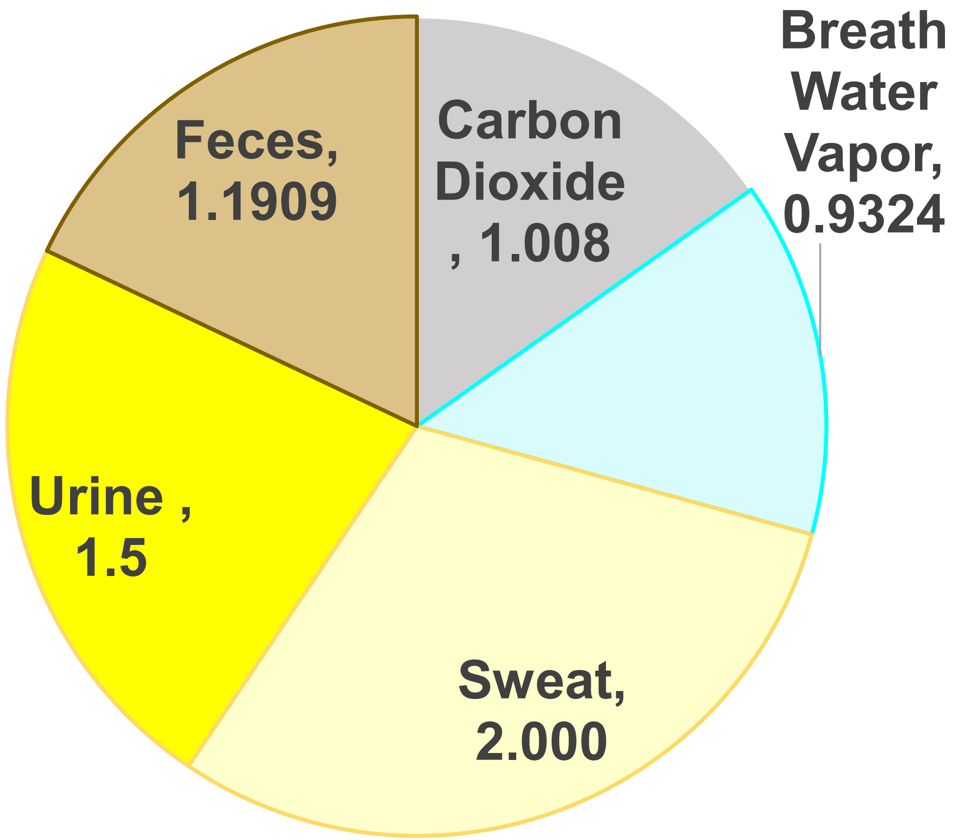


You Excrete what you Eat
Feces 101

- Dietary Fiber passes into feces almost entirely (since it is mostly cellulose)
- The rest=what doesn't end up in Carbon in CO_2, or released in Urine and Sweat
- Water + fiber in feces = easier bowel movements!
- NOTE: Had to make the menu to get here!



Breakdown: Food to Wastes: Masses in kg



Sweat: 2 kg/day, 10% concentration of Urine

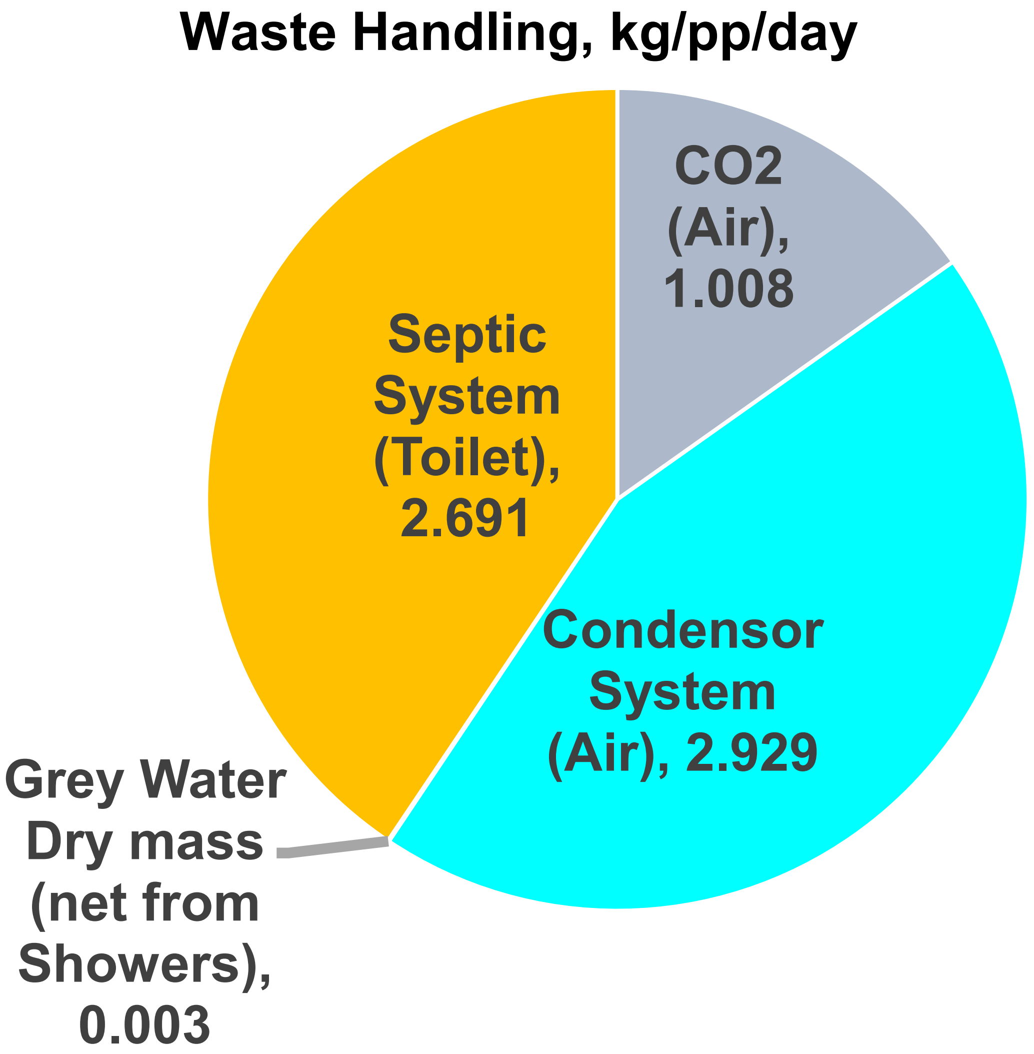
Water in Breath: ~0.93 kg/day

Urine + Feces + Sweat + Breath:

- 5kg Water
- ~0.6 kg Dry Mass
- All non-C,H,O elements end up in Urine and Feces, with a little in Sweat.

Where do human wastes go?

- CO_2 will have to be separated out and (/or directly) sent to photosynthesis for conversion to food and oxygen
- Water vapor from Breath and Evaporated Sweat will be condensed out, UV sterilized, and added to the overall water system as purified water



Mechanisms and Chemistry: Machines

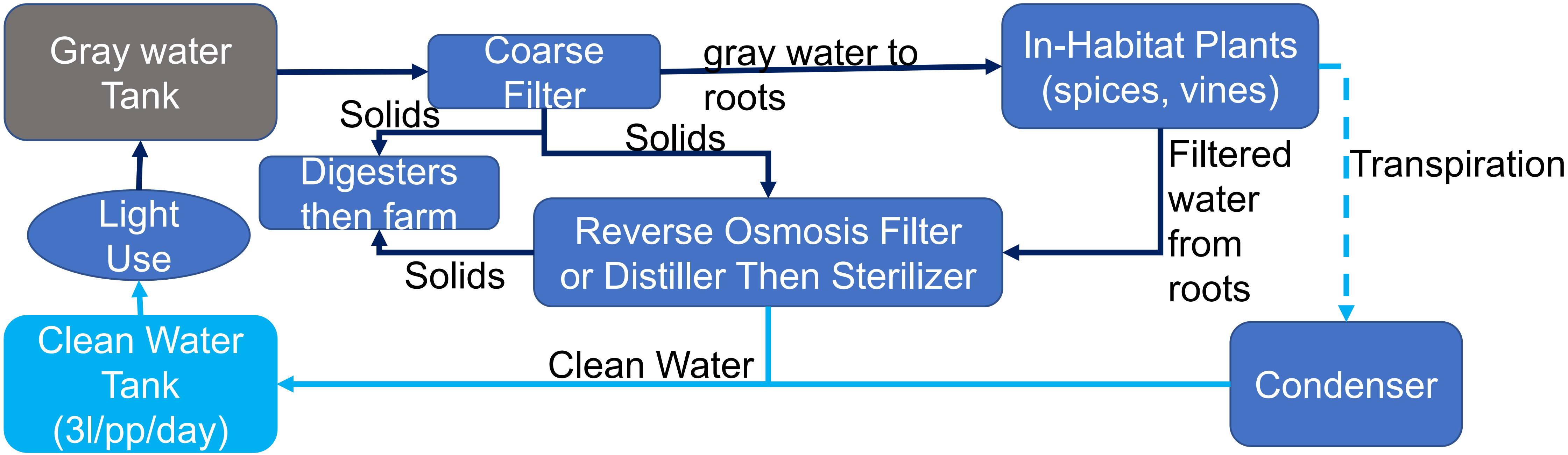
- **Macerating Pumps:** Pumps that chop and blend inputs to a more liquid output
- **Centrifuge Separators**: Use centrifugal force to spin settle out solids and liquids by density.
- **Distillers and Dehydrators:** Use Heat or Vacuum to extract water and other volatiles from sludge or other fluids.
- **Condensers:** Cooling coils or fins and fans to extract vapors from gases, e.g. water from air.
- **Gas Species Separator**: Extracts Carbon Dioxide from Air and sends it to other processes .
  - **Scrubber:** Could be a battery of plants or algae or Zeolite .
- **Reverse Osmosis (R-O) Filters**: use pressure to push water out through a membrane leaving everything else behind
- **Sensors and Valves**: Tied to a control system to control results by monitoring and controlling flows.
- **Settling Tanks:** Containers that use gravity to separate fluids and solids by density over time. Can be used a as digestor with intermittent agitation and temperature control to control output.

Mechanisms and Chemistry: Machines (cont.)

- **Anerobic Digestors**(can be an open format bioreactor): uses bacteria, fungi, or enzymes to break down wastes (or other inputs) into methane and carbon dioxide (or alcohol and carbon dioxide for wine, beer, etc.).
- **Aerobic Digestors** (can be an open format bioreactor too): uses bacteria or other microorganisms **<u>with oxygen</u>** to break down wastes (or other inputs).
- **Aerator:** A pump to add oxygen to a tank or flow. Used in Aerobic Digestors.
- **Pumps for Gasses**, Storage Tanks for Gasses, Valves: Gas Management
- **Membrane Mediated Bioreactor (MMBr):** Uses a high surface area membrane seeded with bacteria or other microorganisms to control the conversion of inputs into outputs.
- **Sterilizers:** Using either UV light, radiation, or heat to kill microorganisms in a fluid
- **Incinerators:** Uses high temperatures and oxygen to convert inputs to carbon dioxide, water vapor, and ash.
- **Thermal Converters**: Convert inputs anaerobically into various outputs by controlling pressure and (high) temperature. Can make biocarbon.

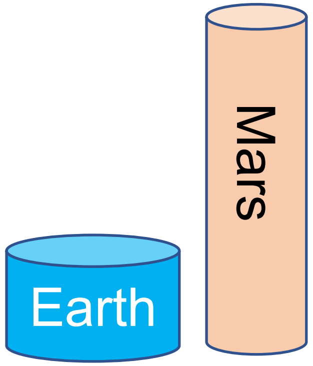
Gray Water Loops

- May Add 4-10 kg per person per day for showers, laundry, food prep, etc.= **Gray Water**
- **Flush water = Black Water**: treated same as Urine or Feces
- Gray Water can loop as below:



Tank Sizing v. Gravity

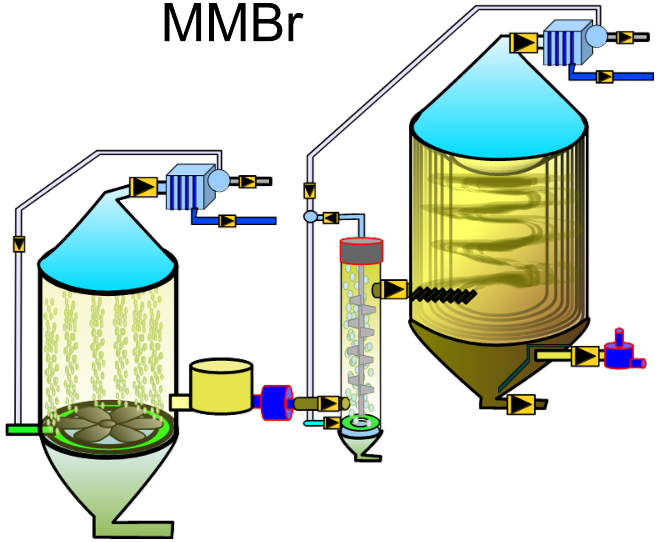
- **Tank Array size = Processing time (days) * volume of (Feces + Urine + flush water) per person* people* volume ratio (i.e. added volume for gases, stirring, at least 150%)**
- -**Settling** will take longer in lower gravities, i.e. 3x longer on Mars, 6x longer on Moon
- +**Bacteria might work** as well or **better** in lower gravities: **solids stay mixed longer**
- -Will take **longer for gases to bubble out** of solutions in lower gravities
- -**Convection** can make cold and hot spots in Moon/Mars gravity
- **Mitigations:**
  - **Centrifuges and dehydrators** to settle out solids when needed
  - **Use vacuum** to ‘boil out’ gases
  - Pumps and **agitators** to stir and move fluids and gases
  - **Membrane Mediated Bioreactors (MMBr)** to accelerate processing time.
  - **Taller columns** for tanks in lower gravity



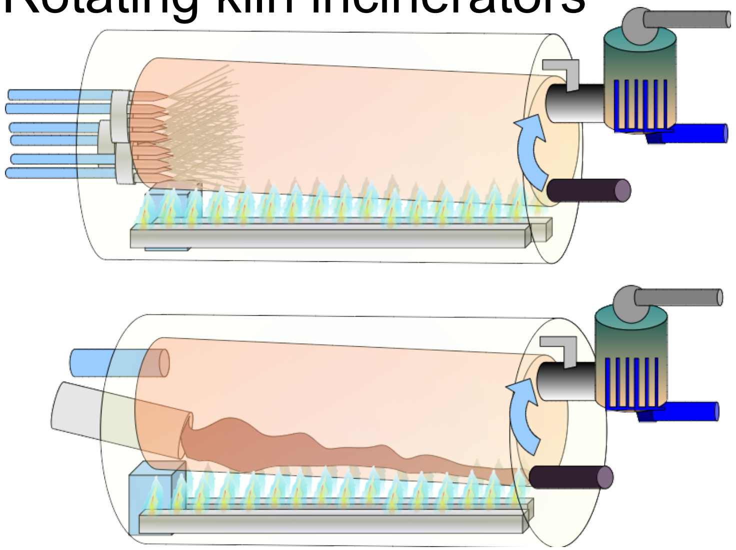
Tradeoffs: Digestor v. Incinerator

- Anerobic Digesters produce methane, which needs to be burned or reacted with O_2 to get the CO_2 and H_2O back.
- Aerobic Digestors and MMBrs are faster than anerobic
- Incinerators:
  - **+Sizing (est.): 0.01 m^3 to 0.02 m^3 per kg processed per hour (based on commercial kilns)**
  - -High heat rejection problems
  - -Minerals in ash are not always in plant available form
  - Careful control can fully burn and limit undesirable results
  - -Requires oxygen to fully achieve outputs
  - Alternatively: Gasification/Thermal Breakdown then fuel cell to produce energy

Aerobic digester combined with MMBr



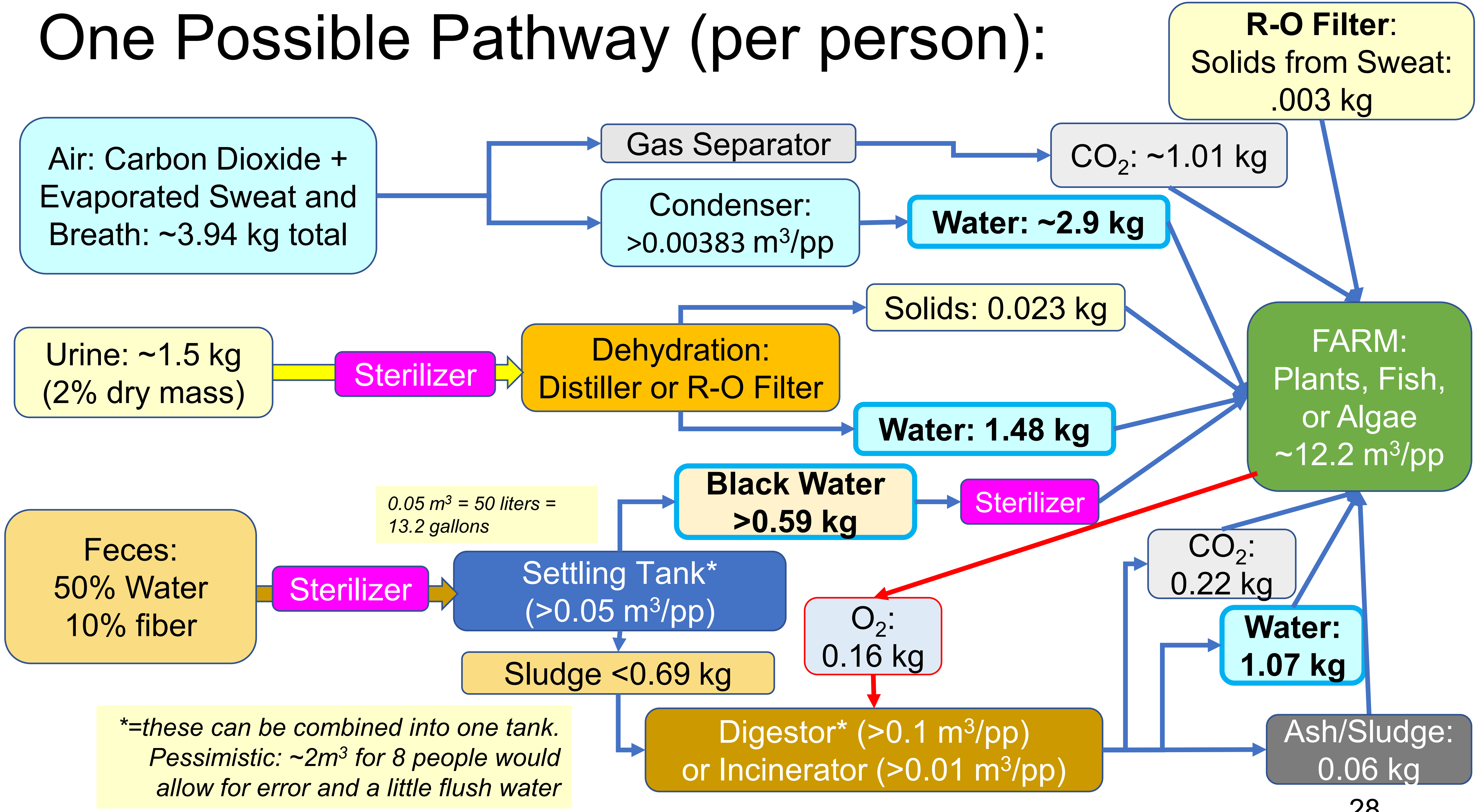
Rotating kiln incinerators



Tradeoffs: Direct recycling via plant transpiration

- Wastewater with low solid loads (after UV sterilization) can be pumped to plant roots in hydroponic or aquaponic farm
  - -Requires a very healthy microbiome in roots to control pH and nitrogen load
  - -Will require stronger control depending on root bed substrate
  - -Pre-filtering/settling and careful bed design needed to prevent clogging in root bed
- Transpiration can be directly condensed and reused in grow area but also in habitat to provide clean water
  - **+Plant transpire >100x the water used for growth.**
- See Gray Water Loop Example (previous slides)

One Possible Pathway (per person):



What can Plants, Animals, or Algae use?

- **Most fruiting plants** (e.g. tomatoes): **1/10th to 1/20th urine concentration**
- Grains, **1/5th Urine**, if genetically altered (see [Roy, Negrao, Tester 2014]…still need to manage salts!
- Black Water: Too many solids **clog** and deoxygenate roots
- **Cyanobacteria** and some species of green and red **algae** are more tolerant, though mineral traces in urine will stress them.
- Animals: **Ammonia** from urine is risk to even saltwater species
- **Salt control of chlorides is the key for plants, and dilution is the response. Also, oxygenate!**

CONCLUSION

- Diet determines human waste composition and treatment.
- **Hydration determines urine concentration**, though even so **urine is too concentrated for direct, undiluted use**
- Condensers recapture sweat and breath vapor. **Sweat and breath release as much water as urine** in many cases.
- **Separation of urine eases processing**, but can be done post flush using centrifugal or mechanical means
- Cellulose/fiber eaten goes into feces. **Cellulose digestion or incineration is critical** to recapturing carbon dioxide and water in closing the mass cycle
- Multiple pathways lead to materials that can be used by the farm: Tanks, filters, distillers, **incinerators, digesters, bioreactors**, and even plants themselves.
- **Trade offs**: **volume**, heat, energy, and crops. **Small pop = incinerate**.

Further work

- Direct use of algae to digest and use cellulose
- Combinations of various pathways for settlements of various sizes
- Effect of gravity on digestion and bioreactors
- Settling column shapes in Moon, Mars gravity
- Enzyme sourcing and recycling
- Crop combinations inside and outside habitat that can use less processed wastes

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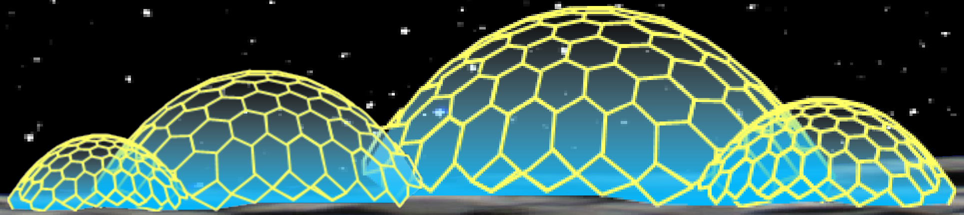
Thank You for Coming!
And remember:
Why do we settle space?
Trillions of Happy, Smiling Babies!

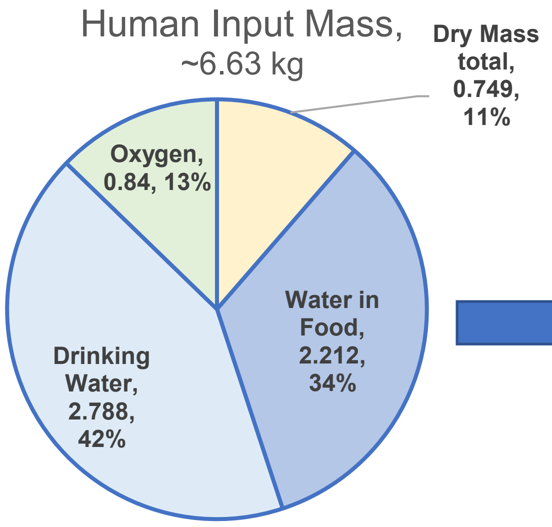


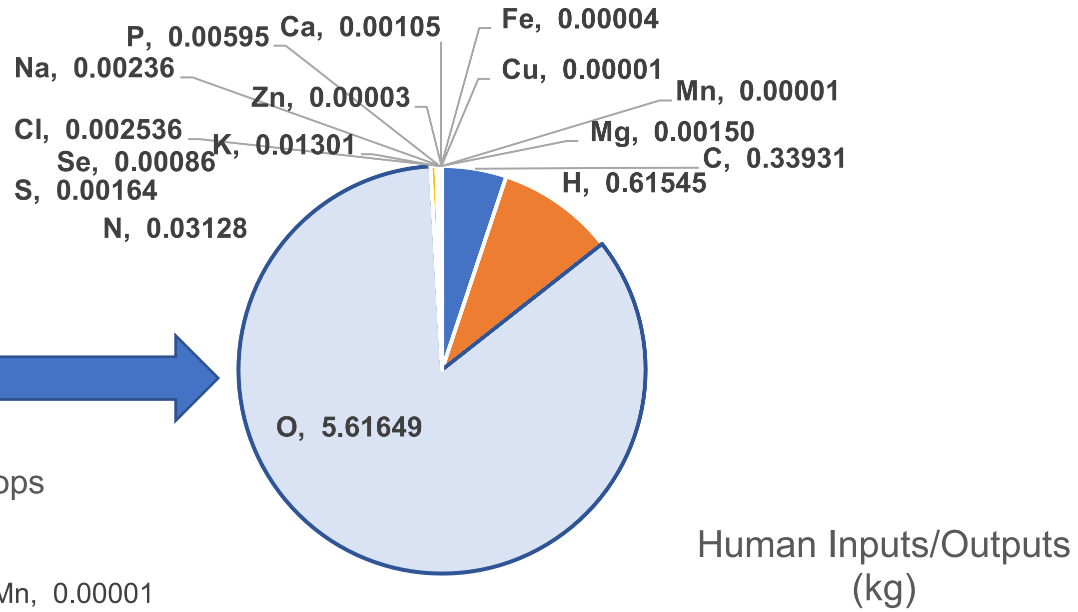
Earth image via NASA

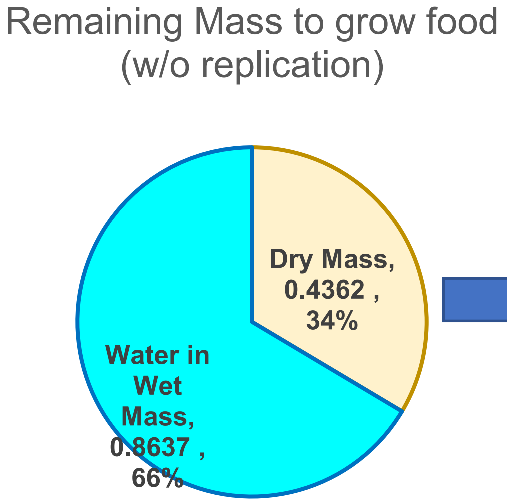
Back-ups

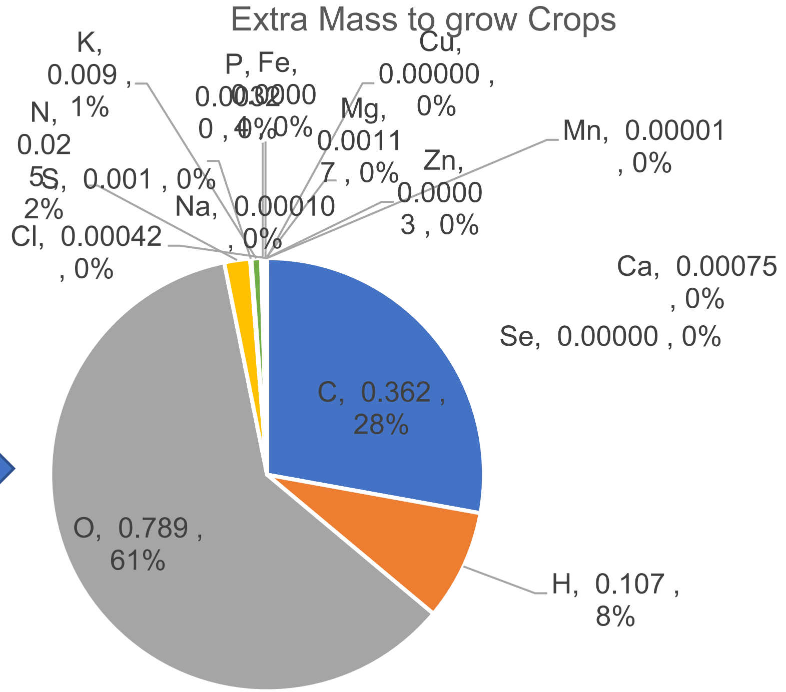
So, actual inputs not counting transpiration….

(and ignoring many other effects…)









Additional Factors not here:

- Fish or Plants in growth to replace each day's crop
- Handling fish wastes
- ***Best to assume the 'farm' handles the inedible parts, fish wastes, etc. for our purposes.***

Abstract

- The Messy Details of Going from Excrement to Entrée
- By Bryce L. Meyer
- Most space research to date has either focused on waste recycling in microgravity to extract water, and expel the rest, or focused on the food growth side, in hydroponic gardens and photobioreactors. These disparate ends ignore the details in the middle, i.e. what turns urine, feces, food waste and other waste types into nutrients for plant growth, clean water, and clean air. What sizes and trades are required for the tanks, pumps, pipes, sceptic systems, incinerators, or bioreactors, to recycle wastes into the inputs for both agriculture and human use. How does this change in low gravity areas like the Moon or Mars? What are timeframes for chemical conversions required, and practical concerns. This paper will cover the masses and chemistry of wastes, existing real world methods, machines and structures, and time required to digest the wastes, and mediation methods to close the mass flow loop to limit resupply, for settlements of various durations and sizes, from small scientific outposts, to village sized long term settlements. Will include sizing of tanks and pumps, energy requirements, biological and non-biological options and tradeoffs, directions for needed research. The messy details matter, and this paper will expose the gap of going from excrement to entrée and provide solutions to get menus from manure in space.