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Project ID: 101081883

P2GreeN

Closing the gap between fork and farm for circular nutrient flows

yellowwater harvesting by gravity-driven collection of source-separated urine from flushing toilets

case study of a broader dwelling development in Hanover

Carsten Beneker
ecovillage (lead of pilotregion Germany within P2GreeN-project)
07th february 2023 at digital zirkulierBAR colloqium

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AGENDA

1. Ecovillage hannover – the case study
2. Motivation for urine recycling
3. The complex chemistry of urine
4. The human factor in design
5. Yellowwater infrastructure design parameters

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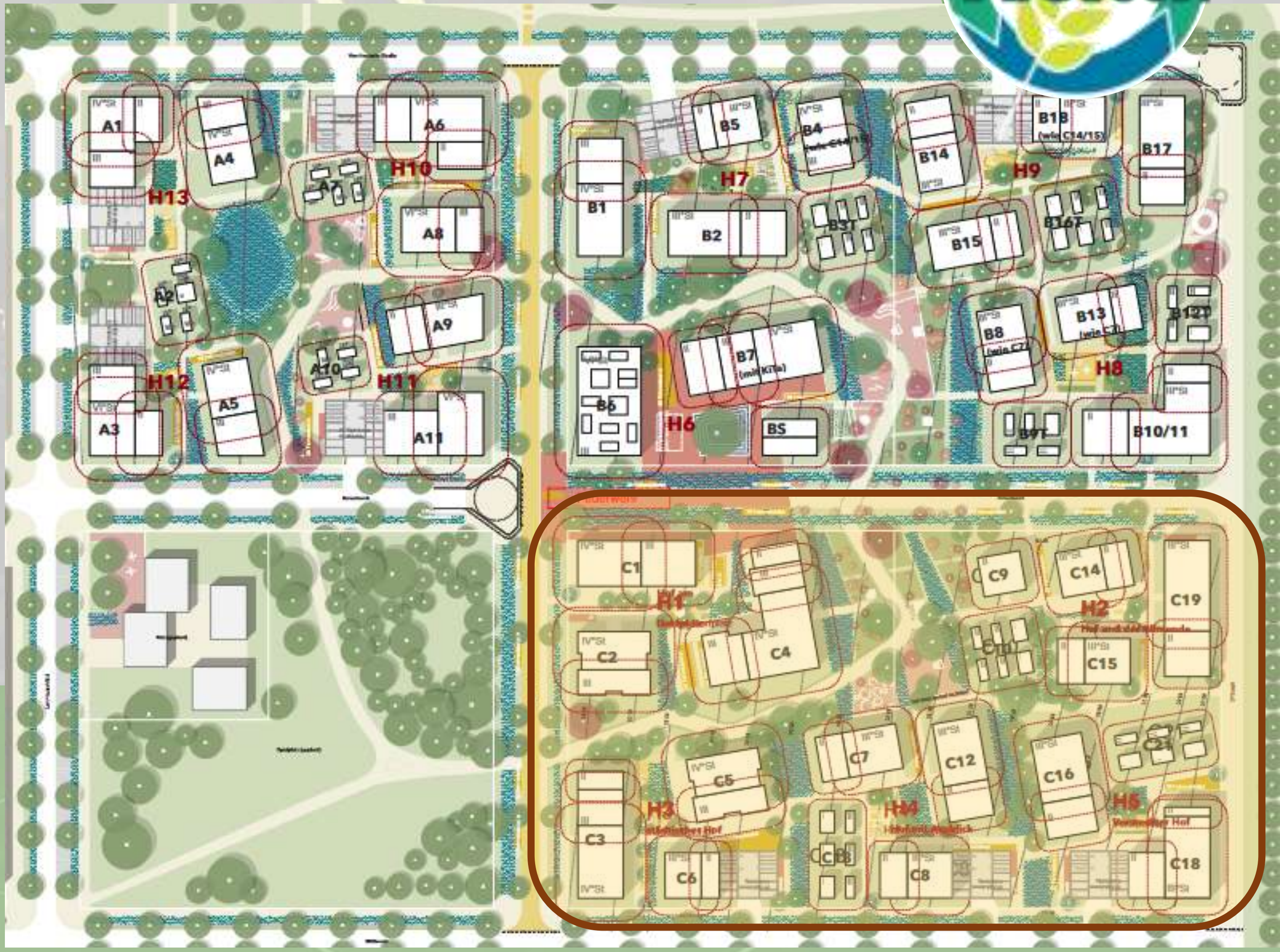
The case study

ecovillage hannover eG (evh) is building an inclusive, sufficient, resilient and **resource-efficient** district for 1000 persons, co-owned by themselves

The mission is to operate and demonstrate sustainable housing that can cope with the challenges of the **future**

The planning is performed as a **bottom-up** approach: Future tenants involve planners to design solutions for their co-created vision



[cityförster / studiomauer, 2022]

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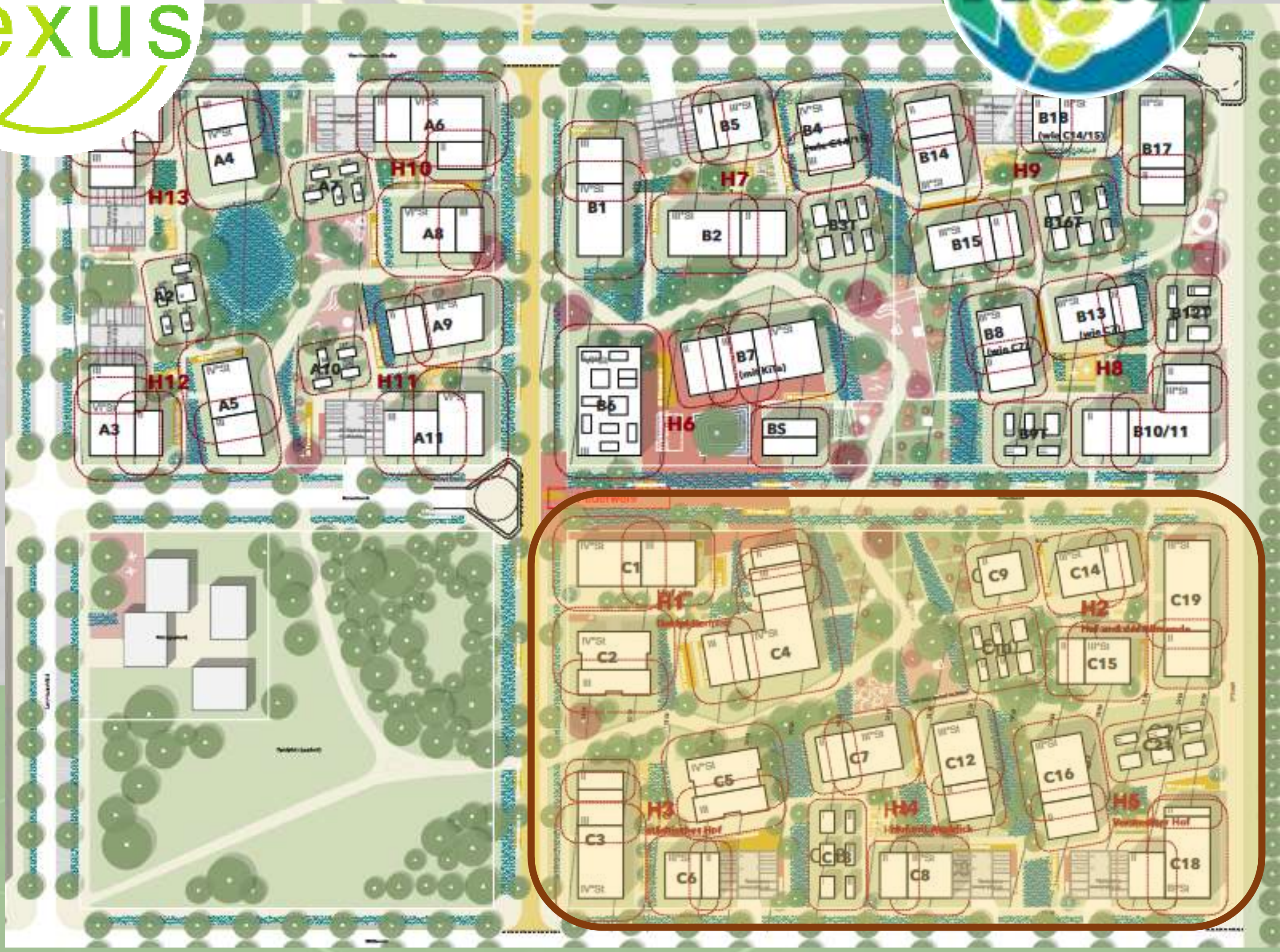
The case study

The results of the co-creative **bottom-up** approach in terms of resilient water infrastructure

- **source separation in all buildings: Brownwater / Yellowwater / Greywater**
- treatment and reuse, where applicable
- pilot building is designed as a zero emission building
- for 50 mobile Tiny Houses private owners are recommended to install indoor dry diversion toilets



[cityförster / studiomauer, 2022]

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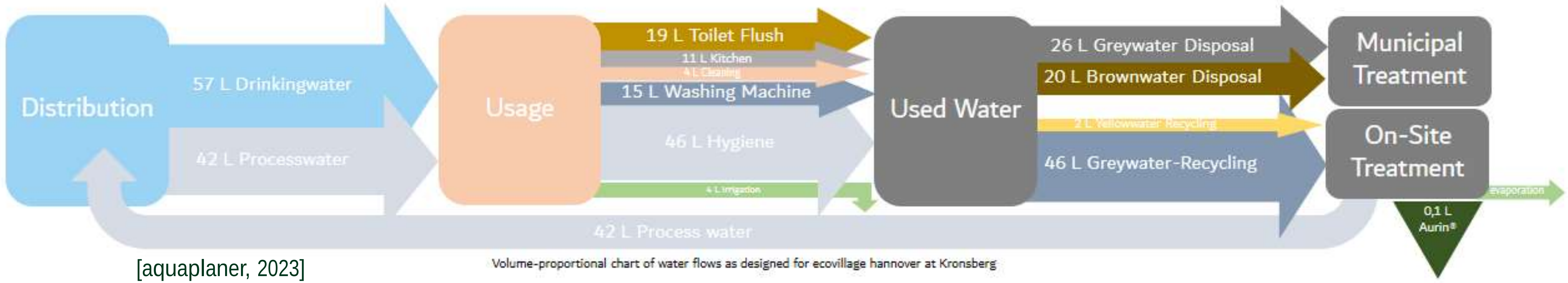

[aquaplaner, 2023]

Volume-proportional chart of water flows as designed for ecovillage hannover at Kronsberg

A urine treatment system with a capacity of 500 l/d will produce Aurin®

- a certified fertilizer -

funded by Horizon Europe Project P2GreeN

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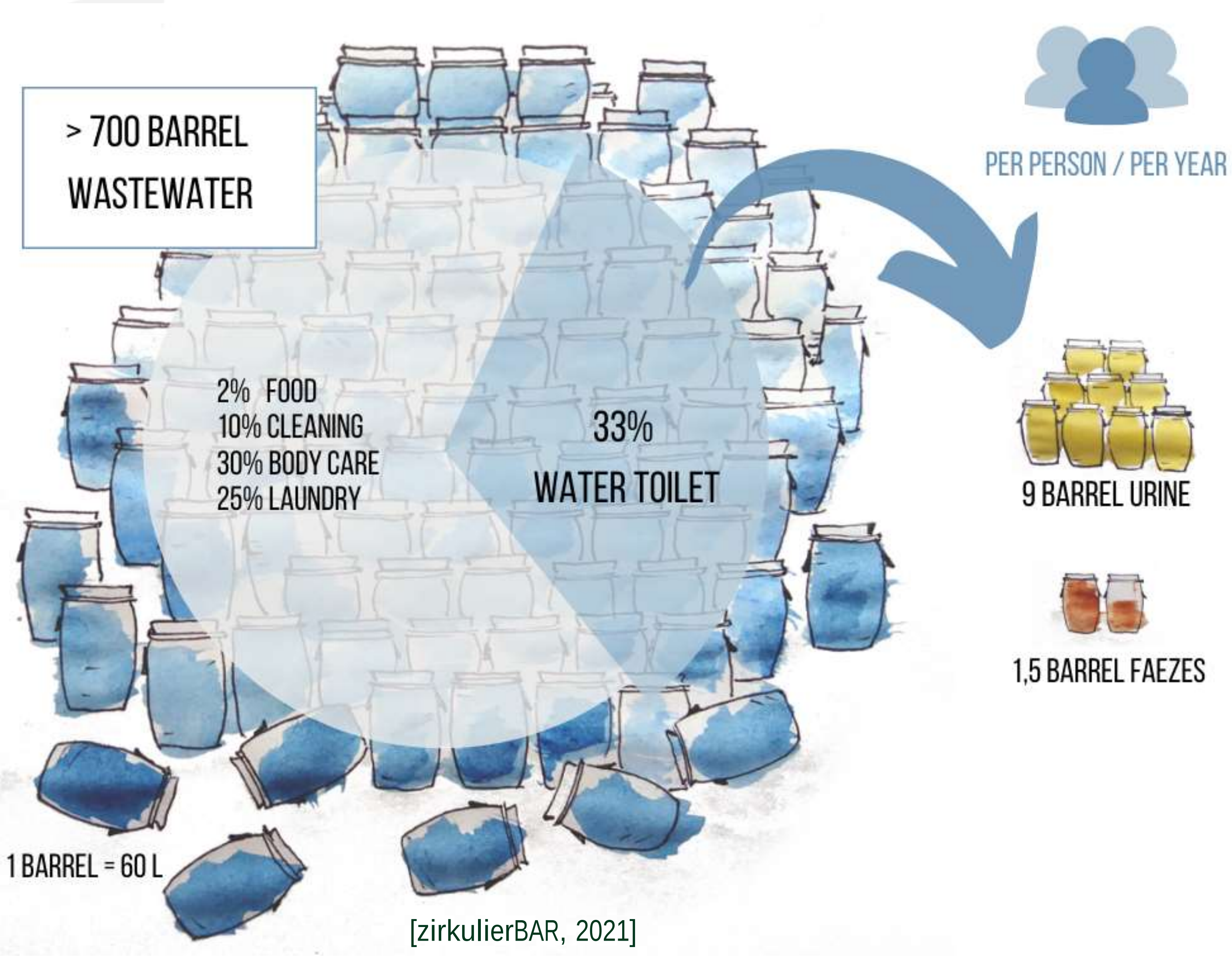
motivation



[zirkulierBAR, 2021]

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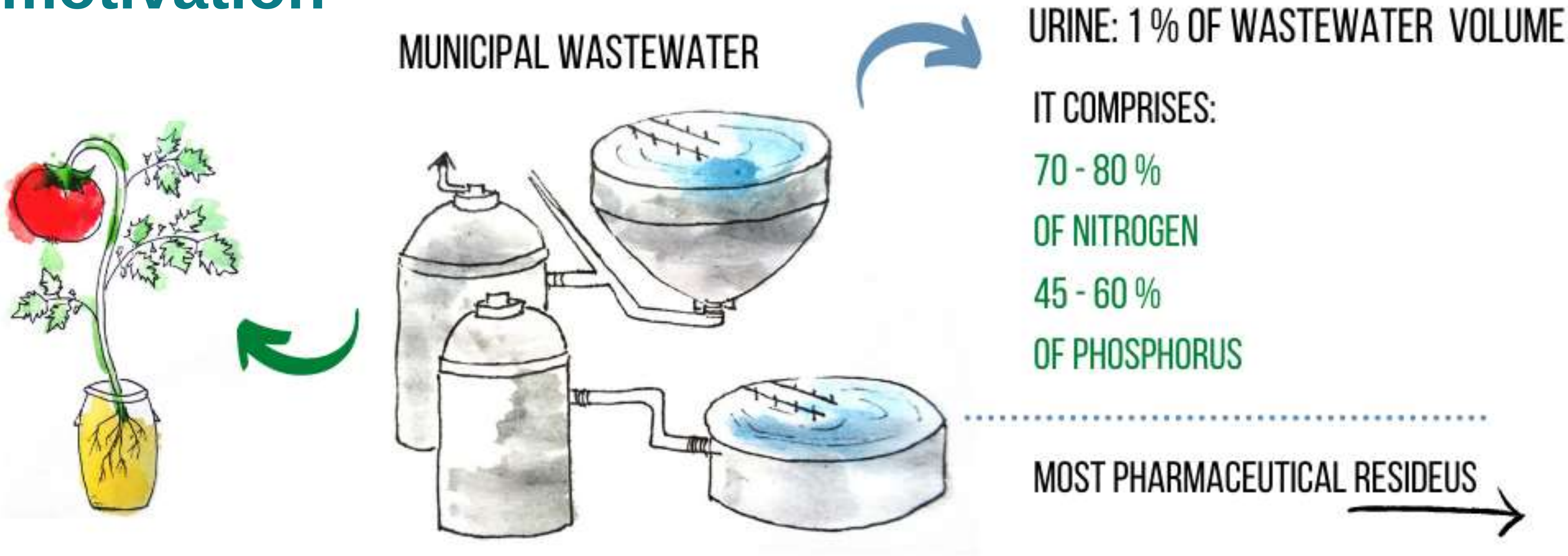
motivation



[zirkulierBAR, 2021]

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motivation

End-of-pipe activated nitrogen fuels algae blooms in our oceas, resulting in fish suffocation [ESA – CC BY-SA IGO 3.0]

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The complex chemistry of urine

The composition of liquid excreta depends on various variables, such as the type of collection, the duration of storage and the environmental conditions (temperature, pH, hygiene, etc.).

Table 1
Measured urine concentrations and literature values [4]

	Ureolysis in collection tank			Ureolysis in pipes		Literature		
	Fresh urine		Stored urine	Fresh urine		Urine		
	Mean	CV%		Mean	CV%	Mean	CV%	Data range
Ammonia[a] ($g\ N\ m^{-3}$)	254	4.5	1720	386	2.5	480	29	—
Urea ($g\ N\ m^{-3}$)	5810	—	73	8750	3.1	7700	20	—
Phosphate[a] ($g\ P\ m^{-3}$)	367	0.9	76	559	4.6	740	14	—
Calcium ($g\ m^{-3}$)	129	1.4	28	168	1.7	190	22	—
Magnesium ($g\ m^{-3}$)	77	2.7	1	121	1.7	100	21	—
Sodium ($g\ m^{-3}$)	2670	—	837	3730	3.2	2800	—	1800–5800
Potassium ($g\ m^{-3}$)	2170	—	770	2250	2.3	2200	—	1300–3100
Sulphate ($g\ SO_4\ m^{-3}$)	748	—	292	1350	0.8	1500	29	—
Chloride ($g\ m^{-3}$)	3830	—	1400	5230	1.6	3800	—	2300–7700
Carbonate[a] ($g\ C\ m^{-3}$)	—	—	966	< 5	—	—	—	—
Total COD ($g\ O_2\ m^{-3}$)	8150	0.6	1650[b]	9700	4.9	—	—	—
pH (dimensionless)	7.2	—	9.0[b]	6.0	0.3	6.2	8	—

[a] Including all system species, e.g. for carbonate $[H_2CO_3^*]$, $[HCO_3^-]$ and $[CO_3^{2-}]$.
[b] Total COD and pH in the collection tank origin from older measurements.

[Udert et al. 2003]

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The complex chemistry of urine

P2GreeN

The **hydrolysis of urea** is one of the dominant chemical changes occurring in a collection system. In the process, **urea is converted into ammonia/ammonium** and carbonate:

$$H_2N(CO)NH_2 + 2\ H_2O \longleftrightarrow NH_3 + NH_4^+ + HCO_3^-$$

The **increase** in the pH value of the urine (usually approx. neutral) **to pH 8.8 to 9.2** is remarkable.
At the same time, the concentration of **gaseous ammonia** and **precipitation** reactions increases (mainly as calcite ($CaCO_3$) and Hydroxylapatite ($Ca_{10}(PO_4)_6(OH)_2$))

In a non-sterile environment, the rate of hydrolysis is dominated by the presence of enzymes (urease; urea amidohydrolase).

Udert [Udert et al., 2003a] determined the rate of hydrolysis. The rate of hydrolysis followed a 0th order reaction (independent of concentration) and was between 1820 and 2770 g N $m^{-3}\ d^{-1}$ at pH 8.9.

The complex chemistry of urine

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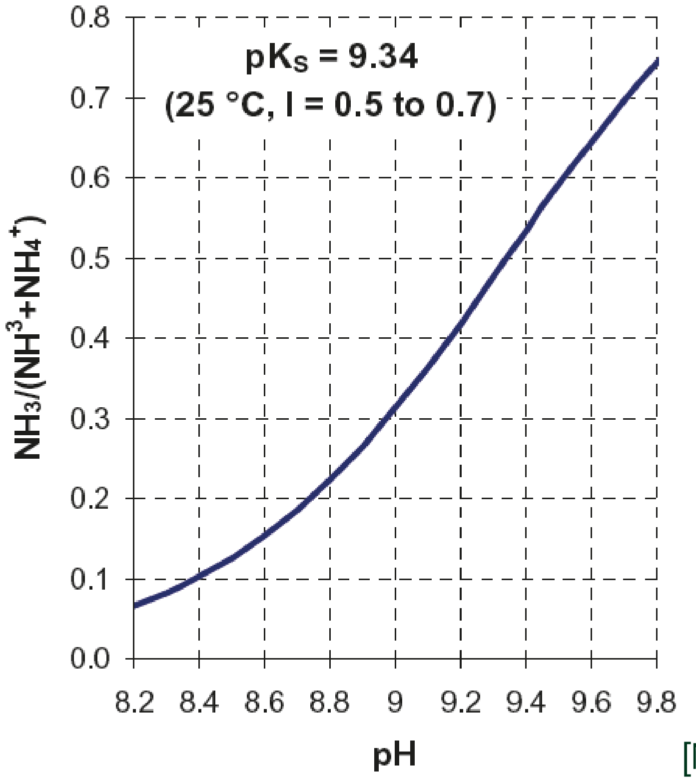
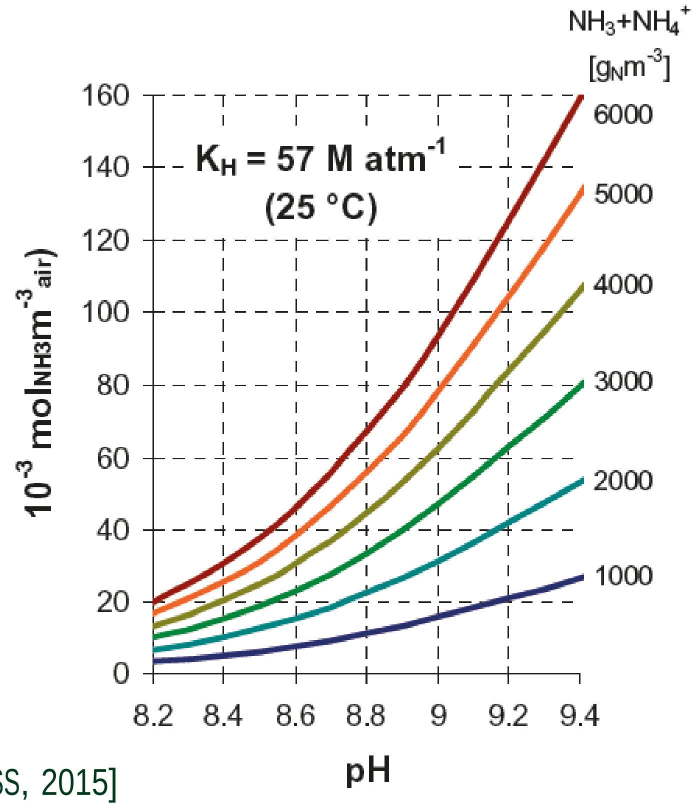
Percentage of ammonia in the hydrolyzed yellow water



equilibrium concentrations in the gas phase for 6 different concentrations (NH_3+NH_4^+) in the yellow water.



[NASS, 2015]

Conclusions

- **In the case of stored urine (pH = 8.8 – 9.2), 20-40% N losses due to ammonia outgassing are to be expected**
- **pH values below 8.4 would be desirable for low NH3-loss**
- **Ammonia concentrations in the air are well above the irritation threshold of approx. 7 mmol NH3 m^{-3} or above the MAK value of 0.8 mmol NH3 m^{-3} (20 ppm, guideline limit value guideline 2000/39/EG)**
- **Explosion range (15-28% by volume) is undershot by orders of magnitude**

The complex chemistry of urine

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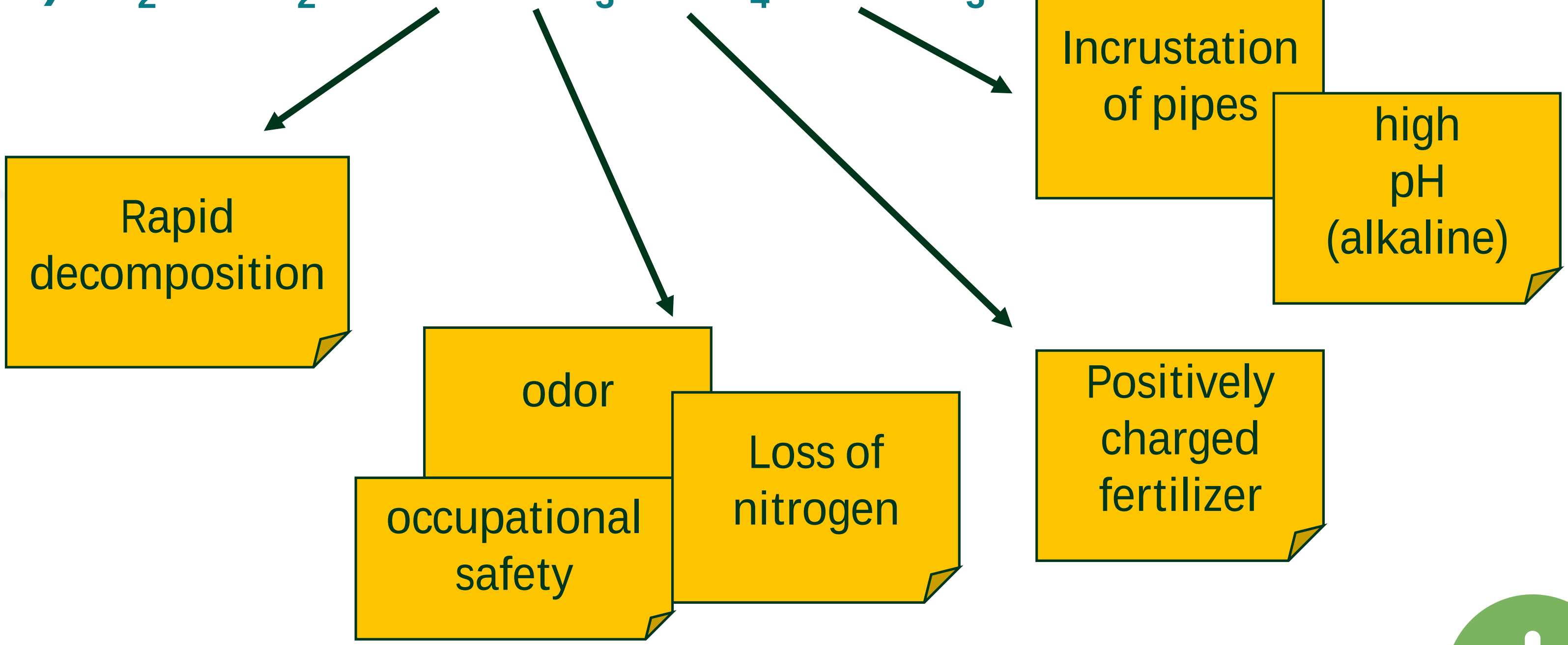


Types of urine ressources based on collection system

Urine

Urine from dry toilets with parallel separation (and urinals)

- Urine and feces are collected separately

[Finizio, 2023]

Percurine

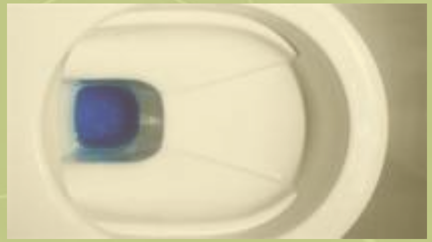
Urine from dry toilets with serial separation

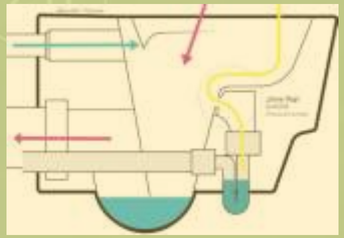
- Urine and feces are collected together
  - Liquid part is drained

yellowwater

Urine from source-separating flush toilets with parallel separation

- Urine and feces are diverted
- Both fractions are diluted with flush water





[Laufen, 2023]

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Yellowwater collection system design

- the human factor -
design numbers based on the user

- **diversion rate →** At which rate is the urine effectively diverted based on user behavior?
- **usage rate →** how much daily urine is donated in the location
- **dilution rate →** What is the usage ratio between (dry) urinals and WC (if applicable)
- **dilution rate →** How many flushes per capita per day
- **dilution rate → treatment efficiency**
- **Diet →** concentration-fluctuation of nutrients
- **Health →** concentration-fluctuation of pathogens and novel entities

[dreamstime.com]

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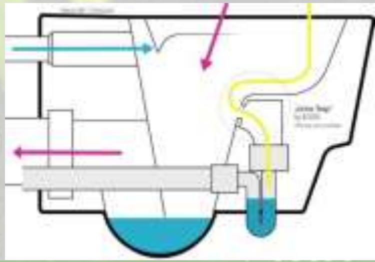
Yellowwater collection system design

- the user interface -
design numbers based on UI

(here: WC type Laufen save!)

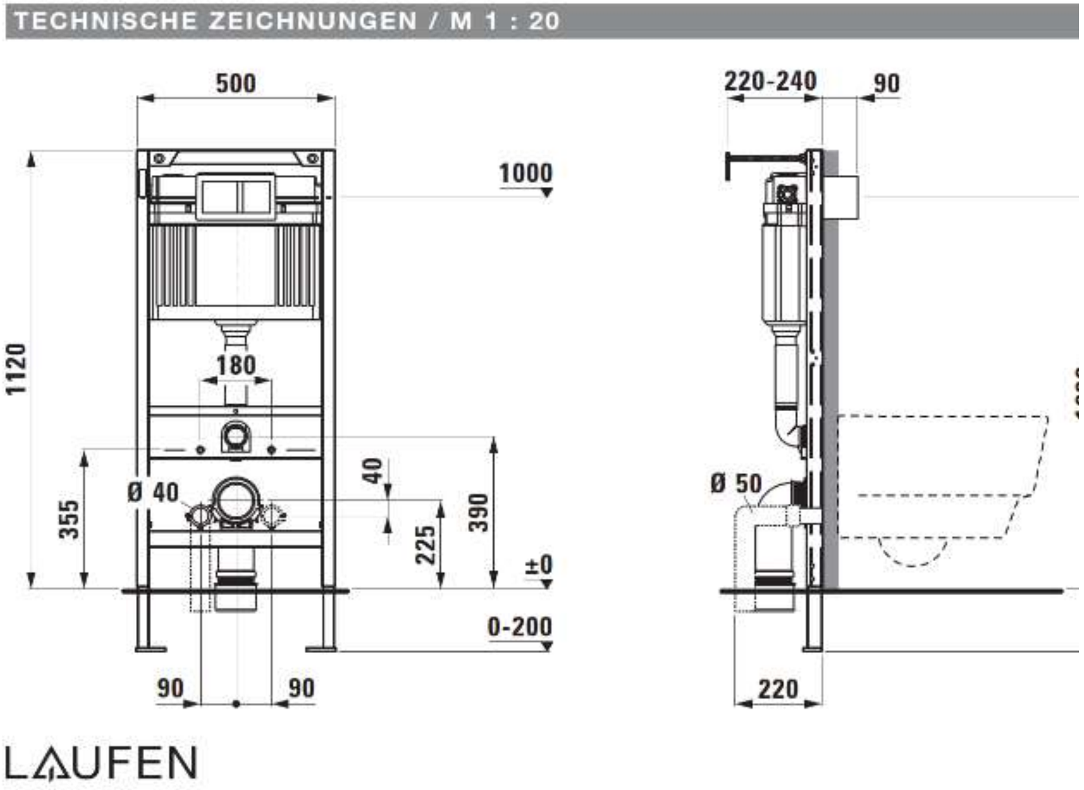
- **diversion rate → approx. 75 % effectively separated by UI**
- **dilution rate → 0,15 l flushing water per usage**



[Laufen, 2023]

→ roughly 1,5 liter of yellowwater per capita and day containing 60 % of pure urine (with varying NPK-concentrations)

Yellowwater collection system design



[Laufen, VunaNexus & Beagengineering, 2022]

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Yellowwater collection system design

odor

Loss of nitrogen

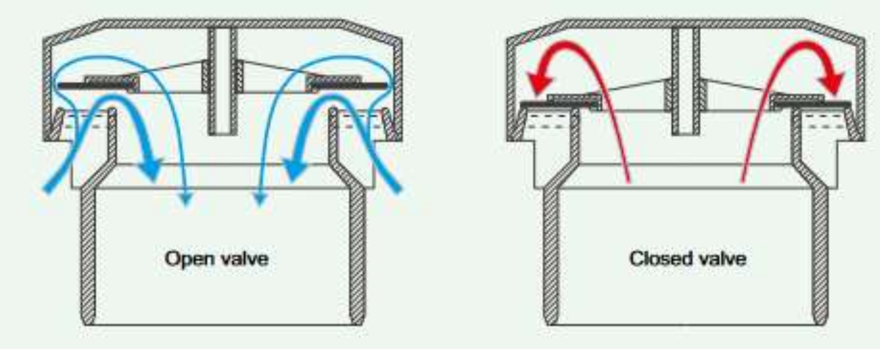
occupational safety

Incrustation of pipes

high pH (alkaline)

Rapid decomposition

- Open vents result in significant nitrogen losses of 44% [Goosse, 2009]
- Yellow water vents should therefore be separated and equipped with a membrane venting valve



[Durgo, 2023]

- Recommendation for pipe dimensions of min. DN 50 for urine drainage
- Design piping network with a slop of min 2,5 %
- The hardness of the flushing water plays a significant role for precipitation chemistry → rainwater beneficial, softening might be favorable
- 90° connections should be avoided and implemented as two 45° connections, if possible
- Train users to clean urine trap with citric acid weekly
- Plan access for inspection & maintenance at crucial spots

- Toilet inventions like sanitation 360 or Blue autarky toilet approach work with a chemical manipulation to stop hydrolysis in-situ

[dw, 2023]

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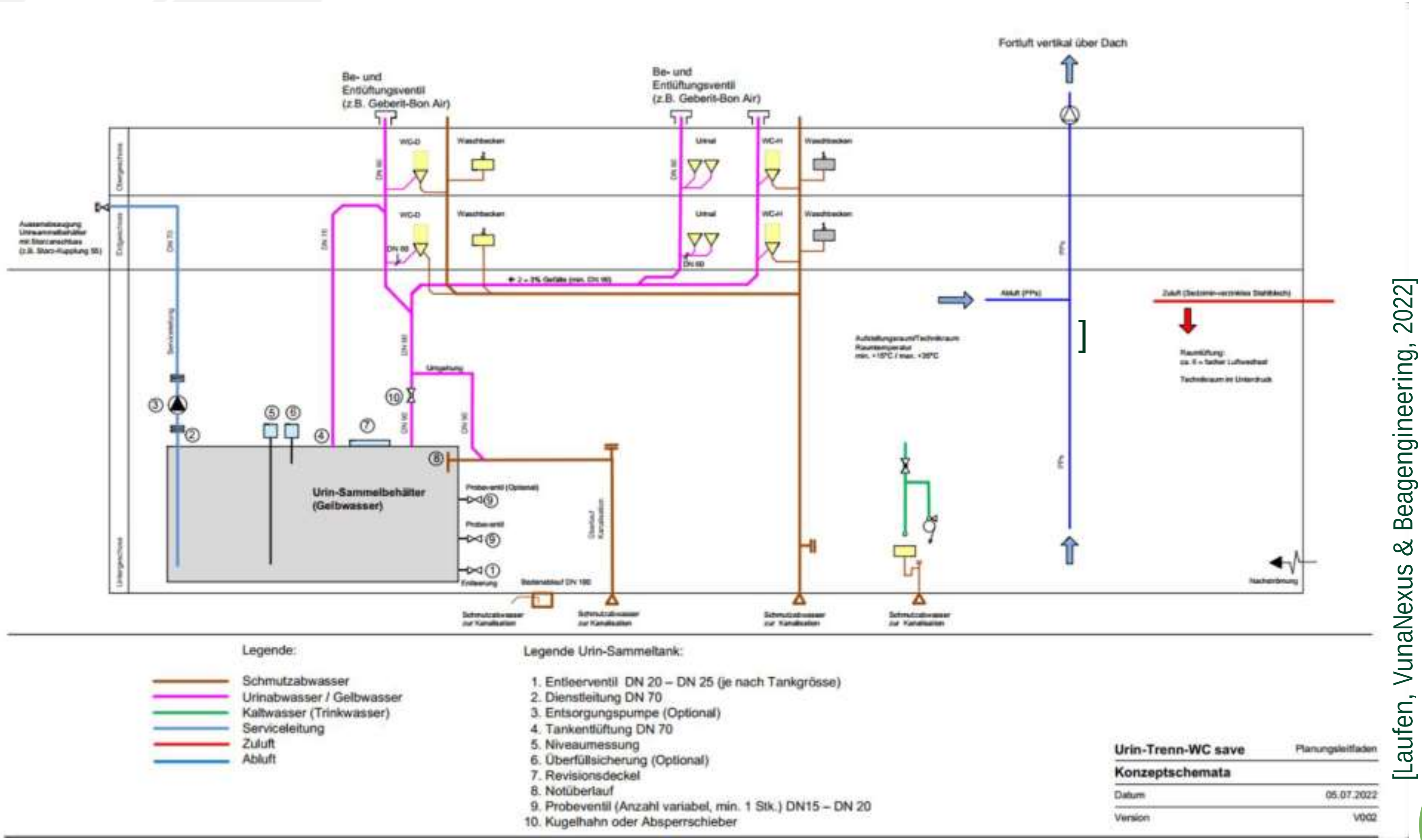
Yellowwater collection system design



[Laufen, VunaNexus & Beagengineering, 2022]

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Yellowwater collection system design

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Table 3-1. Physico-chemical characteristics of fertilizers tested. Three samples of each product were analyzed but as the replicates were homogenous, only the mean value is presented. The density of liquids UBFs was taken as 1 except for nitrified urine for which is 1.14. Dry residue includes crystalized salt. *Not measured because of crystallization. **Value given by the producer (VUNA). Initial urine was the same between stored urine and acidified stored urine and between acidified fresh urine and liquid alkalinized urine. ***As dry matter was performed at 105°C, urea chemical hydrolysis occurs at that temperature. Only trace elements were measured based on dry matter. Then, dry matter and trace elements may have been slightly underestimated.

Parameters		Unit	Nitrified concentrated urine	Stored urine	Acidified stored urine	Acidified fresh urine	Fermented fresh urine	Alkalinized urine	Dehydrated alkalinized urine (lime)	Dehydrated alkalinized urine (lime + biochar)	Fresh urine + woodchips	Cattle slurry
pH		-	**4.0**	**9.2**	**6.5**	**2.1**	**3.5**	**12.3**	**11.2**	**8.9**	**8.2**	**7.3**
Conductivity		mS/cm	43.3	39.0	49.5	16.3	6.2	18.2	16.2	18.9	0.8	3.1
Dry residue (liquid) or dry matter (solid)		g/100g raw material	-*	1.4	3.7	1.8	0.7	2.7	84.0***	82.0***	30.7	5.3
Carbon	**Tot-C**	g/kg raw material	-	-	-	-	-	-	129.0	331.3	153.3	22.7
	Organic-C		2.4	3.3	2.7	5.4	8.3	5.0	82.9	321.0	153.0	22.4
	Inorganic-C		-	-	-	-	-	-	46.2	10.5	0.5	0.5
Nitrogen	**Total-N**		**51.8**	**7.0**	**6.8**	**5.4**	**2.9**	**5.3**	**100.6**	**107.0**	**3.7**	**4.0**
	NH_4-N		26.1	5.0	6.2	0.1	0.04	0.01	0.3	1.3	0.6	1.4
	NO_3-N		25.6	< 0.0002	< 0.0002	0.002	< 0.0002	0.002	0.3	0.7	<0.01	0.002
	Urea-N		0.1	0.6	0.5	4.6	2.4	4.8	95.8	95.2	0.27	0.21
	Organic-N		0.1	1.4	0.04	0.8	0.5	0.4	4.5	10.5	2.8	2.4
Other nutrients	**P_2O_5**		**8.2**	**0.6**	-	**0.6**	**0.5**	-	**14.6**	**16.4**	**0.7**	**1.4**
	K_2O		**32.2**	**2.4**	-	**1.7**	**0.6**	-	**51.6**	**50.3**	**1.4**	**3.4**
	MgO		0.1	< 0.1	-	< 0.1	< 0.1	-	6.5	3.3	0.2	1.0
	CaO		0.7	< 0.1	-	< 0.1	< 0.1	-	273.7	76.8	0.5	2.7
	SO_3		10.9	0.6	-	1.5	0.2	-	14.6	14.8	0.7	0.8
	Na_2O		24.5	3.1	-	2.3	1.0	-	49.4	50.3	1.7	1.2
	Cl-		54.8	3.9	-	2.8	1.3	-	24.8	24.2	0.6	1.2
Trace elements	**B**	mg/kg raw material	9.5	1.1	-	1.4	0.3	-	23.9	21.5	2.4	0.1
	Fe		< 18	< 20	-	< 20	< 20	-	712.0	728.2	31.9	95.5
	Cu		0.34**	< 0.4	-	< 0.4	< 0.4	-	< 2	< 2	0.4	0.5
	Mn		0.4	< 0.2	-	< 0.2	0.3	-	44.7	46.4	14.2	36.4
	Mo		0.6	< 0.2	-	0.9	0.3	-	< 2	< 2	< 0.6	0.01
	Zn		6.5	0.1	-	1.1	1.5	-	12.6	15.6	4.5	1.8
	Se		0.4	< 0.2	-	< 0.2	< 0.2	-	< 1.3	< 1.2	< 0.5	0.01
	As		< 0.2	< 0.2	-	< 0.2	< 0.2	-	1.0	1.0	< 0.3	< 0.05
	Cd		0.03	< 0.02	-	0.05	0.06	-	< 0.1	0.07	0.11	0.04
	Co		< 0.2	< 0.2	-	< 0.2	< 0.2	-	< 0.8	< 0.8	< 0.3	0.02
	Cr		< 0.2	< 0.2	-	< 0.2	< 0.2	-	6.2	2.8	0.3	0.01
	Hg		< 0.0004	< 0.0004	-	< 0.0004	< 0.0004	-	< 0.2	< 0.2	< 0.1	< 0.01
	Ni		0.6	< 0.2	-	< 0.2	< 0.2	-	1.4	< 0.8	< 0.3	0.02
	Pb		< 0.2	< 0.2	-	< 0.2	< 0.2	-	< 2	3.7	< 0.6	0.01

[Martin, 2020]

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sources

All website access from today

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- Durgo, 2023: https://durgo.se/wp-content/uploads/2017/10/Brochure-AAV-Eng.pdf
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- Sanitation 360: sanitation360.se
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Thank you for your interest & questions

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