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Resource recovery from organic household waste

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Sustainable Water and Sanitation, Health and Development

Preface and acknowledgements

This thesis was completed for the partial of a Msc. degree in Sustainable Water and Sanitation, Health and Development at the Faculty of Environmental Sciences and Natural Resource Management at The University of Life Sciences (NMBU) in Ås, Norway. It aims to present a broad overview on resource recovery from organic household waste, such as fertiliser and soil amendment products, by linking technical and societal aspects in terms of opportunities and challenges. The thesis is a desk study where information and data were sourced from peer-reviewed articles, textbooks, policy papers and respected news outlets. Sections of the thesis were also sourced from previous papers I turned in for courses THT383 and GEO220.

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"The saviour is either the insignificant thing itself, or else arises out of it" Carl Jung

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Abstract

Population growth, water scarcity, loss of agricultural soils and desertification resulting from climate change and unchecked resource extraction are all inextricably linked to social issues such as poverty, disease and gender. Irresponsible nutrient flow management leading to pollution of scarce freshwater sources, coastal areas and soils is a hindrance to achieving our goals of combating climate change, providing inputs for agricultural production enabling food security, true access to potable water and achieving societal equity. Understanding possible sources of pollution as well as interactions between pollutants, the complexity of often ignored third-party effects and working toward creating and streamlining legal frameworks enabling the implementation of resource recovery on national and local levels can play a vital role in meeting the social and environmental challenges we face. There are fears associated with treatment efficacy and removal of pollutants such as pathogens, heavy metals, micro- and nano-plastics, PPCPs and POPs in reuse of resources such as urine and faeces from human origin. These fears are rarely evidence based, and a great body of research shows they have little merit. Alternative fertilisers such as urine, struvite and algae biofertiliser provide a source of vital nutrients. Urine particularly provides nitrogen, while struvite acts as a slow-release phosphate source. Alternative fertilisers such as struvite, urine and algae bio-fertiliser are safe and nutrient-dense products capable of replacing or supplementing mineral fertilisers. In conjunction with decentralised, circular sanitation systems, resources may be recovered while limiting pollution caused by, as well as freshwater used in conventional flush and forget sanitation systems. UDDTs allow for fertiliser and compost production and can be made more efficient by dehydrating urine using water extraction, nutrient extraction or a combination of these methods. This facilitates transport while reducing cost. Biogas production through anaerobic digestion of organic household waste produces energy in the form of combustible CH_4, and a nutrient rich liquid for use in alternative fertiliser production. While algae is an excellent source of fertilizer, it also acts as a biostimulant and can contribute to improving soil physical and chemical characteristics such as soil aggregation. Likewise, composted faeces following urine diversion offer carbon-rich soil amendment useful in combating soil degradation. Streamlining international and national legal frameworks by creating guidelines on testing and limit values for nutrients and pollutants is necessary to ensure safety and marketability of recovered fertilisers and soil amendment products. A 2020 DIN specification, 91421:2020-12, provides such guidelines. This brings us a step closer to achieving increased resilience and increasing circularity of local and global economies.

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1 Introduction

There are 8 billion people sharing this planet, concentrated on less than 7% of global ice-free lands (Smith et al., 2022). A planet with finite resources, incompatible with the imperative for infinite and exponential growth built-into the capitalist economic model. The general consensus amongst economists is that the economy must grow by >3% annually so large corporations can maintain revenue (Hickel, 2015). This means that every 20 years, the economy is expected to double.

Considering our current population growth rate of 73 million per year, the next time the economy doubles there will be nearly 1.46 billion more humans on this planet. Humans that need to access nutritious food and potable water and defecate without contaminating the environment or becoming trapped in an endless cycle of disease and poverty. They, alongside the people already inhabiting earth, also require more than this: a dignified life that is not centred around mere survival.

No more than 2.5% of the water on planet Earth is freshwater (Hendriks, 2010). Of this 2.5%, 69% is bound in polar ice, 30% in groundwater (>50% of this is brackish) and a mere 1% is made up of atmospheric, soil and surface waters. An increase in both socio-economic development, coupled with climate change will lead to more pressure on freshwater resources, even where improved economic status leads to less pressure on land. Water stress and pollution is most concentrated in 20% of ice-free lands (Smith et al., 2022). Water stress occurs when a location's annual supply drops below 1700 m^3/p-1, while water scarcity occurs when it drops below 1000m^3/p-1 (Landon, 2006). About 10% of the world's population lives under conditions of high to critical water stress, 67% of whom inhabit urban areas. The average city dweller uses about 140 litres of water a day, much of which goes toward simply flushing the toilet through conventional sanitation systems. This is often followed by insufficient treatment of sewage and eventual pollution of land and water.

Some 70% of water is used for agricultural production, with 39% of global ice-free land made up of crop and rangelands. A mere 55% of this is used to grow food directly consumed by humans (Cassidy, 2013). Had crops been grown exclusively for direct human consumption, global calorie availability could increase by 70%. Following WWII, recovering economies saw massive growth in fertiliser use until the collapse of the Soviet Union and subsequent removal of subsidies caused a decline due to price inflation (Brown, 2014). From the mid-90's, emergent economies fueled an increase in use once more. Today, facing challenges of supplying food to an ever-expanding population and the depletion, desertification and erosion of soils resulting from conventional agricultural practices as well as the impact of climate change, the continued provision of nutrients to the agricultural sector is vital to our ability to feed ourselves. Equally, this is an opportunity to revisit the status quo out of necessity and attempt to think in less linear, more circular terms about mismanaged and valuable resources. Sources include runoff from agricultural lands, animal husbandry, atmospheric deposition and the discharge of partially treated wastewater into water bodies. The flow of these macronutrients into the environment has exceeded the planetary boundaries suggested by Rockström et al. (2009) as safe operating spaces for humanity. Continuing to maintain the status quo increases the risk associated with irresponsible nutrient flow management.

1.1 Nitrogen

Though plentiful in the atmosphere, some 75% of nitrogen (N) for agronomic purposes is sourced through the Haber-Bosch method –which relies upon natural gas; a finite resource and contributor to global warming. About 2% of global energy is used for production of N using the Haber-Bosch method. (Martin et al., 2023); fixing hydrogen with atmospheric nitrogen producing ammonia (NH3+). The remaining 25% of N comes from biological fixation in the nitrogen cycle.

Per EU directive 91/271/EEC -urban wastewater treatment, 70-80% of N must be removed from WW effluent discharging into waters; leaving some 20-30% to be discharged untreated. At WWTPs, denitrification is often considered best practice, relying on autotrophic nitrification and heterotrophic denitrification, but is both energy intensive and tends to only allow for 10% N recycling (Martin et al., 2023). Additionally, nitrous oxide gas (N_2O) emissions from denitrification processes at WWTPs is a significant contributor to GHG emissions (Martin et al., 2023; Valkova et al., 2021). According to the IPCC (2013), N_2O has a 265x higher global warming potential than CO2 and the GHG's concentration continues to increase at a rate of 2.5% annually (Enhalt and Prather, 2018).

1.2 Phosphorous

Phosphorous is another vital macronutrient discovered by Henning Brand in 1669, a German alchemist and apothecary, and named after the much-poeticised morning star Phosphoros (from the Greek for "light bearer"; Latinised: phosphorous. Brand isolated P from urine by boiling it into a paste and heating said paste until white crystalline P (White phosphorous;(WP)) remained; His attempt at producing the philosopher's stone by doing this was, as far as we know, unsuccessful. The element was long before observed to emit its own "light" and was supposedly harnessed for use in "perpetual lamps" already in the 4th century AD by early Christians (Aldersey-Williams, 2011).

In 1974, the mechanism by which this happens was finally demystified: when the element comes into contact with oxygen, the combustion of short-lived oxides on the element's surface gives it the quality of phosphorescence /luminescence. There are two forms of phosphorous: WP discovered by Brand; an extremely volatile and toxic form used in weaponry, fireworks and others application making use of its spontaneous combustibility; Red phosphorous (RP), a non-toxic and stable form used in matchboxes and which does not display phosphorescence. The bulk of P, however, is used in fertiliser manufacturing and as nutritional supplements in animal husbandry.

Manure, blood, potash and phosphate rich bones and teeth (hydroxyapatite; calcium phosphate) were up until the 1840s the dominant fertiliser sources. Potash, from the Dutch potaschem, was traditionally produced by using iron pots to first soak organic material (often wood) ensuring water solubility and then evaporating the liquid –leaving potash for application as fertiliser.

P is often the main limiting macronutrient of productivity in freshwaters, as it is the least abundant (Wetzel, 2001). It is also the most studied and there exists a great amount of quantitative data on seasonal distribution and influx from surrounding catchments and to receiving watercourses from drainage. >90% of P within freshwaters occurs in the form of organophosphates, these play several important roles within the body (e.g., binding the double helix of DNA; energy provided and exchanged by adenosine triphosphate (ATP), which also acts as a coenzyme).

It is soluble inorganic orthophosphate $[PO_4]^{3-}$ which is bioavailable for uptake in biota. Particulate P is strongly adsorbed to organic compounds as well as minerals such as clay, which may travel long distances through rivers and streams. In Norway this has been a water management issue, with P-sorbed clay draining into waters and transported great distances via rivers, leading to eutrophication.

1.3 Phosphate ore mining and radionuclides

Some of the largest geological deposits of phosphate ore, occurring as hydroxyapatite and fluoroapatite – mostly as sedimentary marine phosphorite, but also in some igneous deposits (e.g., Brazil), exist in China, Morocco, the Moroccan-occupied West Sahara, South-West Asia and the United States; some 70% of which is in the MENA region. These deposits are non-renewable and tend to have high heavy metal content, particularly of cadmium (Cd).

Radioactive isotopes tend to be concentrated in areas where natural phosphorous reserves are mined. Phosphate ore contains high concentrations of radionuclides arising from the decay series of the radioactive isotopes uranium-238 (U-238) and thorium-238 (Th-238). When it is mined, processed and loaded for transportation, dust particles enter terrestrial and aquatic environments and accumulate in soils, the atmosphere and biota. A 2007 study found that the main source of polonium-210 (Po-210) (used to murder journalist, critic of Vladimir Putin and former KGB agent turned MI6 agent Alexander Litvinenko), and lead-210 (Pb-210) accumulation in soils and plants was radon (Rn) gas and its decay products (Othman and Al-Masri,2007). In fact, radon gas is considered to have the highest potential for pollution in mine workers through inhalation and in the environment due to its motility. The dominant source of Po-210 in soils and bedrock is uranium ore –albeit at very low concentrations (0.1ppb) (Długosz-Lisiecka, 2016), within the atmosphere its main source is the release of radon gas from soils; a daughter within the U-238 decay chain (Illustration X). In drainage ditches surrounding agricultural lands onto which phosphate fertiliser has been applied over time, high concentrations of U-238 have been reported, as well as in surface waters and shallow groundwater, while radium (Ra) isotopes increase with depth (Barišić et al., 1992) and Cs-137 measured in drainage ditches. Effluent directly discharged into coastal waters also enhance radioactivity in sediments and marine organisms. In many areas, phosphate mining operations and plants are situated along coastal areas for processing purposes, providing a direct route for phosphogypsum into aquatic environments and sediments. The radionuclides Ra-226 and Po-210 tend to be concentrated in solid waste by-products of the phosphate mining industry, phosphogypsum, while U-238 may be distributed directly onto agricultural lands via mined phosphate fertiliser application; as uranium remains in the phosphoric acid phase (Długosz-Lisiecka, 2016; Phosphogypsum leaches radionuclides into groundwater (Othman and Al-Masri, 2007). Health hazard is also climate dependant, as drier regions allow for more dust transfer into the atmosphere and inhalation by workers and their families, often residing nearby mines –e.g., at Palmyra, before the war, in the Syrian Badia (Othman et al., 1992).

1.4 Simplified agriculture

The success of simplified agriculture (conventional scientific agriculture) is quantified by its output, granted there exists a commodity market and competitive pressures. The failures associated with such schemes can according to Scott (1998) be traced to deeper systemic failures. They often come to light only when surrounding circumstances reveal them and are assumed to be dealt with once the failures are addressed – e.g., the faulty cog in the machine has been mended. It is not quite as simple when dealing with more complex systems that are both technical, socio-institutional and environmental.

One of the elements at work in the systemic failures of agricultural plans is the sharp focus on production and productivity. Yield and profit take precedence over all third-party effects, forcings or externalities (Scott, 1998). These “externalities” occur as an outcome of another event or as a result of production and/or consumption. Among others these may be direct impacts on soil structure over time, longer term forcings exacerbating the impact of climate change, by-products of fertiliser extraction and production, eutrophication of waters and the social impact of everything from depletion of agricultural lands to the commodification of water -the list would be very long. Chronic renal failure (kidney failure) in Sri Lanka, for example, is an externality of the Green Revolution due to the cadmium (Cd) content of triply superphosphate added and accumulated in soils (Bandara et al., 2010). Oversimplification can have complex and unforeseen consequences.

Other factors are the discrediting and erasure of knowledge developed and gained outside the scientific paradigm. This gives the illusion of an unwillingness on the part of farmers to incorporate non-expert knowledge into practice. What is more often the case is that the experts themselves are unwilling, while farmers are open to receiving knowledge from all places and in all forms.

The presumptions on expertise are also inherent in systemic failure when they reinforce and serve an invested party. Institutions, government entities and non-governmental organisations (NGOs) may in fact perpetuate global issues to maintain influence within the “development” sector (Bertini et al., 2023). The rift between humanitarian and developmental efforts, commonly referred to as *"silos"*. Additionally, there are assumptions about the context in which agricultural plans are applied; based on the development of scientific agriculture in the temperate West (Scott, 1998). Blueprint solutions are as unfortunate as they are ubiquitous, and despite the best of intentions may lead to detrimental consequences in the long and short-term.

The fact that simplified industrial agriculture came to rely heavily on machinery means standardization became necessary, a focus on monocropping and an (successful) attempt at creating an assembly line mode of agriculture. Crops were to be adapted to suit the machine via engineering, not the other way around. Compact cropping and uniformity of shape and size became and are desirable, in addition to suitability to (often predetermined, high nitrogen) fertiliser and pesticide inputs. Plant varieties which more easily fit into this model, such as maize and wheat, are selected over those perceived as harder to integrate into a mechanised system –those requiring increasing the system's complexity. They are hybridised and selected and bred for machine purposes as well as outward aesthetics.

Such prioritisations cause a loss of biodiversity, breeding knowledge and, perhaps most importantly, adaptive potential in the face of climate change; due to the loss of landraces and wild varieties with higher tolerance to variables such as salinity and drought This is *by design*, as diversity is incompatible with the machine. In fact, the United Nations Food and Agriculture Organisation (FAO) estimates that over the last century there has occurred a 75% loss in crop biodiversity, as well as an animal breed every month in the last decade. This comes alongside the loss of 38% of global arable land since The second world war and an ever-increasing global population, projected to reach 9 billion by 2050. Figure 1 shows population count versus arable land in hectares per person between 1950 and 2050 (Gupta et al., 2021). Currently, 75% of the planet's food comes from 12 crops and 5 animal species (UN, 2019). On their own, wheat, maize and rice supply all of 60% of plant-sourced energy and protein.

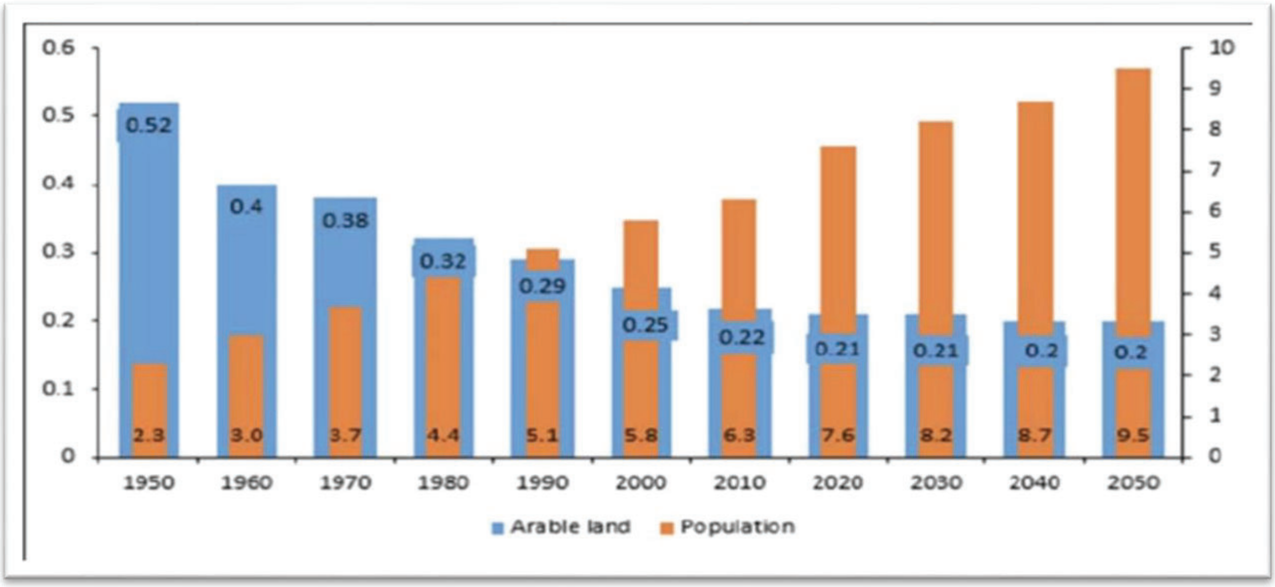


Figure 1. World's population in billions against arable land in hectares per person a year (Adapted from Gupta et al., 2021).

There is a clear need to veer away from the kind of linear thinking built into simplified agriculture while rehabilitating depleted soils. Recovery of resources such as fertiliser and soil amendment products from organic household waste using circular systems is a promising way of achieving this goal. We must however acknowledge the risks involved, even when exaggerated, to combat real and imagined fears hindering acceptance at a local, societal and policy level. Some pathogens and pollutants of concern are provided in the section below.

2 Pollutants of concern

2.1 Pathogens

Important transmission routes for pathogens from excreta are fluids, fingers, flies, floors and fields; eventually ending up in food and making their way into the body (Landon, 2006). Improvement in public water sources does not automatically result in an improvement in private transmission of disease, there is therefore also a need to focus efforts on improving private sanitation such as providing alternatives to open defecation; a source of a continuing cycle of disease transmission. Though the practice has been significantly reduced in the past two decades, some countries still have a very high percentage defecating openly (e.g., 49% in Benin, 63% in Chad and 65% in Niger), disproportionately in low-income and already vulnerable communities (World Bank, 2022). With a global estimate of 419 billion people still practicing open defecation (WHO, 2023). It is estimated that nearly 400,000 children under five died of diarrheal diseases in 2019, and an average of 700 continue to die every day.

As an example, Ascaris (a non-segmented roundworm) in the Nemathelminth (or Aschelminth) family, Trichuris (whipworm) and Necator (hookworm) are primary helminths of concern and are the most common sources of infection caused by inadequate sanitation and treatment of wastewater. However, various helminths in the Nemathelminth and Plathelminths (flatworm) and Nemathelminths (non-segmented roundworm) families are reported in north Africa, the far east and certain Asian nations (Jimenez-Cisneros and Maya-Rendon, 2007). Though few die directly from infection, the malnutrition, exhaustion and growth retardation caused (Landon, 2006) lead to death indirectly. The infections caused by the microscopic eggs of these worms are known as helminthiases (Jimenez-Cisneros and Maya-Rendon, 2007); it is worth noting that the worms themselves are not microscopic. As Ascaris and Trichuris tend to be transmitted via egg faecal-oral routes, improvement in hygiene; granted safe water sources exist, can greatly reduce their occurrence. Ascaris Necator, on the other hand, is transmitted via hookworm eggs hatching on moist soil and the penetration of Necator worms into skin (Landon, 2006). Here open defecation, application of sludge and disposal of wastewater on or near agricultural lands is a transmission route, meaning infection is far more likely (and does occur almost exclusively in low-income nations) in more rural areas without access to improved sanitation, and in which sewage sludge or wastewater is insufficiently treated before disposal (Jimenez-Cisneros and Maya-Rendon, 2007).

An effective strategy in combatting the spread of helminths in vulnerable communities is the use of preventive chemotherapy; it is however short-term, and the rapid rates of reinfection mean there is a need to focus efforts on improving water, sanitation, wastewater treatment and hygiene (Strunz et al., 2014). A prerequisite for improving hygiene is, of course, providing access to safe water and improved sanitation via WASH programmes.

Bacteria; such as Salmonella, Viruses; such as Hepatitis A/E, Parasitic protozoa; such as cryptosporidium parvum and somatic coliphages are other pathogens to take into account.

2.2 Heavy metals and organometallic compounds

Metals and metalloids make up 75% of the periodic table and can be, but are not always, essential macro and micronutrients with varying toxicities at certain concentrations. The term *Heavy metals* has met its fair share of criticism. The classification of heavy metals was long based -and often still is, on the relative density of a metal to that of water (>5:1) -alternatively a specific weight of 5g/cm3, until 1980 when Niboer and Richardson proposed a replacement based on biologically and chemically significant grouping of metal ions. Heavy metals, considered environmental pollutants, are united by their ecotoxicological impact and chemical behaviour -as opposed to density; though they remain a heterogenous group of metals which vary in chemical properties, biological impact and ecotoxicological effects (Sharma and Agrawi, 2005).

Niboer and Richardson proposed that metals be divided into three classes, depending on their binding preferences; covalent and ionic –generally dependant on the difference in electronegativity between atoms. A difference of <0.4 indicates nonpolar covalent binding, between 0.4-1.7 generally indicates a polar covalent bond and an electronegativity difference >1.7 tends to mean ionic binding. These are, respectively: *class A* (oxygen-seeking), *class B* (nitrogen or sulphur-seeking) and *borderline* (or intermediate) (FIG X). It is the latter two classes one might classify as heavy metals, with *class A* metals generally considered micronutrients, so long as they do not exceed requirements which may also lead to toxicity. Though Nieboer and Richardson suggested the term be abandoned altogether, it will be used throughout this paper due to its continued prevalence in the literature, as well as colloquial use and understanding, though its definition will be as described above.

Class A ***Oxygen seeking***	***Borderline***	***Class B*** ***Sulfur or Nitrogen seeking***
	Zinc (Zn)	
Calcium (Ca)	Lead (Pb)	Cadmium (Cd)
Magnesium (Mg)	Iron (Fe)	Copper (Cu)
Manganese (Mn)	Chromium (Cr)	Mercury (Hg)
Potassium (K)	Cobalt (Co)	Silver (Ag)
Strontium	Nickel (Ni)	
Sodium (Na)	Arsenic (As)	
Berilium (Be)	Vanadium (V)	

Table 1: Oxygen, sulfur or nitrogen and borderline heavy metals. Adapted from Fergusson (1990).

Heavy metals tend to be concentrated in soils and aquatic environments, with some in the atmosphere in the form of aerosols and volatilised vapour (Sharma and Agrawi, 2005). They are non-biodegradable and may therefore persist in the environment. Anthropogenically driven concentration of heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), arsenic (As) and nickel (Ni) in soil has in many places reached toxic levels (Sharma and Agrawi, 2005). In soil, they originate either from parent material via weathering, or contamination by anthropogenic activity. Anthropogenic sources may be primary such as fertiliser application in agriculture and secondary like smelting, aerosol deposition and mining.

The dominant heavy metals in soil originating in parent material are lead (Pb), followed by cadmium (Cd), arsenic (As), antimony (Sb), selenium (Se) and Mercury (Hg) (Fergusson, 1990); A reminder that these metals are also naturally occurring despite their possible ecotoxicological effects. Often, these metals will appear in conjunction with sulphide minerals (Walker et al., 2012). Concentrations derived from parent material do not necessarily reflect concentration in soils derived from parent material, as their individual solubility will determine the extent to which they are transported or retained. Furthermore, for some of these pollutants, anthropogenic activity's contribution significantly exceeds parent material contribution -as is the case with Pb; this depends on how widespread the use of such metals is in human activities (Fergusson, 1990). It is also important to note that many heavy metals are considered micronutrients and are vital to the health of flora and fauna (e.g., Cu, Co, Ni, Mn, Fe, and Zn) (Sharma and Agrawi, 2005). Heavy metals such as Cu, Zn, Fe, Mn and Mo play essential roles as constituents of enzymes and in redox reactions. It is only when their concentrations exceed requirements that they become toxic but may also become toxic due to potentiation of toxicities.

Terrestrial plants, being unable to get up and walk about, come in contact with and absorb heavy metals from their growth medium through their roots. These are taken up into the plant and affect flora by altering antioxidant levels, as well as physiological mechanisms. This includes impact on *"photosynthesis, gaseous exchange and nutrient absorption, and... reductions in plant growth, dry matter accumulation and yield"* (Sharma and Agrawi, 2005, p.1), as well as reduction in nutritional values, and to a lesser extent via deposition of particulate aerosols or atmospheric vapours onto foliage. Aquatic plants, on the other hand, are partially or fully submerged and adsorb metals more directly. Pathways into humans may be through ingestion of plants and animals in which metals have accumulated or via inhalation of particulate aerosols and vapours. Inorganic fertiliser is well known to contain heavy metals, of which Cd, Pb and Hg are generally of the most concern. None of these are especially available for plant uptake, but accumulate at higher concentrations, interacting with biotic and abiotic factors.

The main mechanisms responsible for the ecotoxicological impact of heavy metals are covalent binding to organic groups and binding to nonmetal parts of cellular molecules (Walker et al., 2012). Through binding to organic groups, lipophilic compounds and ions are formed capable of breaking the blood brain barrier. Tetraalkyl lead $Pb(C_2H_5)_4$, tributyltin oxide $[(C_4H_9)_3Sn]_2O$, methyl mercury salts and methylated forms of arsenic are highly toxic organometals formed via this mechanism.

Thomas Midgley was the first person to test Dec– tetra-ethyl lead (TEL; ethyl) for use as an antiknock agent in 1921 (O'Brien and Gethin-Damon, 2011), by 1923 leaded gasoline had been commercialised. This has earned Midgley the title of someone *"responsible for more damage to Earth's atmosphere than any other single organism that has ever lived."* (Walker, 2007). Fears concerning safety surfaced almost immediately as hundreds of workers began dying at the DuPont TEL manufacturing company; deaths occurring after workers became *"Gripped by violent bursts of insanity, the afflicted would imagine they were being persecuted by butterflies and other winged insects before expiring, their bodies having turned black and blue."* (Kitman 2000a). In 1971, Japan set a limit of 0.3g/L lead in fuels and began marketing unleaded fuels the following year. In 1975-76 lead paint was banned in the U.S. and a process of phasing out leaded gasoline began, as legal basis and toxicity were established. At this point a mean lead blood level of 48 µg/dL was likely present in the U.S. population (Robbins et al., 2010) during years of maximum exposure; leading to developmental and behavioural issues in children, such as brain damage and hypertension following them into adulthood. These values are today considered lead poisoning. Mean blood values decreased as leaded gasoline was slowly phased out. The average U.S. citizen had in 2011 *"a blood lead level under 2µg/dL. The level that triggers public health action to prevent further exposure is 5µg/dL."* (O'Brien and Gethin-Damon p.3). The decline in percentage atmospheric concentrations of lead correlated positively with percentage decline in sale of leaded fuels.

In the 1980s, Pb had an anthropogenic enrichment factor (AEF) of 97% (Walker, 2012) due to its widespread use as a gasoline additive functioning as an antiknock agent between 1923-1976, in addition to insecticide for caterpillar control. Fears surrounding the accumulation of lead in soils and waters led to regulation regarding the use of Pb in gasoline and paints with a global shift toward unleaded fuel. In May of 2021, the United Nations Environment Programme (UNEP) declared an end to the era of leaded fuel, years after its environmental and psychological impact from cars. Unfortunately, much of the damage had already been done. An example of Pb poisoning, the Flint water crisis of 2014-2015, is provided in the appendix.

Methyl arsenic has historically been used in herbicide and dimethyl arsenic as a defoliant in the Vietnam war. Arsenic pollution in Bangladesh and east India is provided as an example in the appendix.

In the 1980s, Cd had an AEF of 89% and it is one the heavy metals of greatest concern and presence in fertiliser. Plant uptake of Cd is often greater in soils that have low OM and clay content (so low CEC) with which to bind (Agritopic, 2021). Uptake is also higher under saline conditions; where the salt CdCl+ is taken up more easily than Cd2+, under acidic conditions and at low Zn concentration. Various plants react differently to Cd, with root vegetables, leafy greens, vegetable oil seeds, legumes, peanuts and tobacco having the highest concentrations.

When ingested, it accumulates in the liver and kidneys and can cause damage to their functioning. As mentioned earlier on, mineral fertiliser application in Sri Lanka during the Green Revolution led to the spread of chronic renal failure. Phosphate fertiliser contains higher concentrations of heavy metals in general and Cd in particular due to mining of phosphate ore, which can be extremely variable in Cd content. The island country of Nauru's phosphate rock contains upwards of 500-600 mg Cd/kg P. The case of itai-itai disease in Japan can be found in the appendix.

Aluminium (Al) is an element we are heavily exposed to in the age of aluminium. With its relative density of 1.5, it would not qualify as a heavy metal per the old classification; the serious ecological and toxicological consequences wrought caused by its accumulation do. Al can worsen or lead to the development of conditions such as Parkinson's disease, Alzheimer's, alcohol use disorder, autism spectrum disorder and multiple sclerosis; which also means there is promise in using Al levels as markers to monitor and identify such conditions (Bryliński et al., 2023). Al3+ influx into acidified water bodies do. Al3+ pollution has led to massive fish die-offs by binding to the negatively charged gills of fish and suffocating them. Al may also be deposited in the brain and play a role in the development and onset of Alzheimer's.

Tributyltin oxide $[(C_4H_9)_3Sn]_2O$, abbreviated (TBTO), and other organotin compounds are used in antifouling agents preventing marine growth on the surfaces of ships and fish cages, as well as insecticide targeting boring animals in timber production.

Mercury, a metal so dense (13.534g/cm3) Pb may float on its surface, has historically been used to treat syphilis, in makeup, thermometers and as a skin lightener alongside, of all the things to lather on your body, arsenic. While liquid Hg can be ingested in small amounts without detrimental consequences -liquid Hg was prescribed for constipation up until the late 1800s, organomercury with its lipophilicity and bioavailability pose grave ecotoxicological risk to biota (Walker et al., 2012). There is evidence of mercury accumulating in individuals on the autism spectrum, likely leading to belief in a false causality within the antivaxx community -mercury does not *cause* autism and had that been the case antivaxxers might be better served pointing their pitchforks at Tuna fish instead.

Methyl mercury $[CH_3Hg]^+$, created through anaerobic bacterial processes in soils and sediments is more bioavailable than liquid mercury and can accumulate up the food chain leading to disabilities and, in the worst of cases, death (see the Minamata Bay disaster in appendix). In 1914, methylmercury was commercialised as seed coating due to its powerful antiseptic and disinfectant properties, as well as it's fungicidal and herbicidal qualities (Schartup, 2022). In fact, organomercury was still being used as seed coating in the UK as late as 1993. Currently, small-scale artisanal gold (Au) mining, upon which >100 million people rely as their primary source of livelihood is the single greatest source of mercury in the atmosphere. To rid Au of impurities, it is mixed with Hg forming an amalgam in which gold will dissolve but most impurities will not. It is then heated to evaporate the mercury, leaving behind relatively pure gold. The ratio of Hg lost to Au produced can using some methods be as high as 15:1 (Yoshimura et al., 2021).

Thallium; a water soluble, odourless and flavourless white powder, is highly toxic and easily taken up by the body through inhalation, skin and gastrointestinal tract absorption (Kemnic and Coleman, 2018). The occupational exposure limit is 0.1mg/m3 on skin for 8hrs/day. At a concentration of 15mg/kg it is lethal to humans, though Tl can kill at lower concentrations as well. Due to its highly innocuous appearance and the difficulty in its sensory detection, Tl has historically been used as an intentional poison. The first symptoms are innocuous enough –influenza and food-poisoning-like symptoms (gastrointestinal). Symptoms then progress from gastrointestinal, to neurologic, to ocular to dermatologic.

One near-miss example of unintentional poisoning that truly stands out comes from Siberia in June of 2004, when 25 Russian soldiers found a can containing a mystery white powder and elected to roll it into their tobacco cigarettes, snorting it and using it as a talcum powder substitute –the can contained thallium and earned the soldiers an honourable mention (as they survived) at the 2004 Darwin Awards.

The most famous example in fiction comes from Agatha Christie's novel *The Pale Horse (1961),* in which symptoms of thallium poisoning revealed the pollutant as the murder weapon. Christie's novel is credited with saving at least three lives (Aronson, 2007) due to people, having read the detective novel, recognising the symptoms described; some of which were hair loss and streaks on fingernails.

Thallium remains, however, a severely understudied source of pollution (Voegelin and Zierl, 2019). While the typical range found in soils is between 0.1-1mg/kg, the discovery of soils with values >1000mg/kg in Erzmatt, Switzerland near Buus has led to research on the solubility of Tl in both soils and water. This resulted in an observed distinction between deep and topsoil in terms of Tl behaviour. While Tl in deep soils was strongly sorped to the clay mineral species illite -essentially integrated into its structure, topsoils showed sorption to manganese oxides; in both cases limiting solubility and bioavailability. Soil composition therefore plays a great role in the solubility and toxicity potential of the pollutant. Tl was found to show solubility in rivers and streams of the Baselbieter Jura region in Switzerland. Though Switzerland has not specified limits on Tl content in drinking waters, concentrations fell well within limits set in the U.S. (2mcg/L).

Increasingly heavy metals and pharmaceuticals have become causes for concern in water courses. These respectively inorganic and organic pollutants can be excreted from humans and concentrated in wastewater effluent, affecting ecosystems in a variety of ways and providing a pathway to human exposure through fertiliser application. Important non-point sources of metals to the environment are runoff from urban areas, combined sewage systems and effluent from wastewater treatment (Gilmour and Riedel., 2009). Effective removal during treatment processes should be a priority alongside reuse of macronutrients.

2.3 Organic micropollutants

2.3.1 Pharmaceuticals and personal care products (PPCPs)

Pharmaceuticals are a large group of highly varied organic compounds designed to induce a biological effect on humans and other animals, be it to treat illness or induce psychoactive effects (both legally and illegally).

In addition to being found in surface waters, pharmaceuticals have been measured in groundwater and marine ecosystems (Jones et al., 2007). Consumption is only likely to increase with increased average lifespans and the publishing of the human genome in 2001. If our purpose is reuse of valuable nutrients contained within the wastewater while increasing the purity of a resulting fertiliser or soil amendment, solutions such as source separation with urine diversion or anaerobic digestion are preferred. Butkovskyi et al. (2015) have found that a combination of aerobic and anaerobic treatment increases pharmaceutical removal from wastewater.

Despite low concentrations measured in surface waters, toxicity may be additive or antagonistic, but also synergistic. In other words, potentiation of toxicities can occur due to the presence of a great number of both pharmaceuticals and environmental chemicals in surface waters (Walker et al., 2012). Negative impacts of pharmaceuticals include stunted growth, carcinogenicity, feminization of fish and bioaccumulation (Halling-Sørensen et al.,1998).

A proportion of pharmaceuticals ingested or administered to humans and other animals ends up in wastewater effluent. A mixture of various pharmaceuticals and PCPs may cause potentiation of toxicities, an issue also arising when dealing with heavy metals (Section number). A comprehensive study by Kolpin et al. (2002) examined and quantified the occurrence of pharmaceuticals and hormones in 95 U.S. watercourses between 1999-2000. They found that despite concentrations being in the ng/L range, the bulk of examined chemicals were not regulated and thereby had no guidelines on limit values. The amount of chemicals found in given water samples was still alarming –they found a median of 7 pharmaceuticals in individual samples, with some containing upward of 38 per sample.

These drugs are metabolised within humans and other animals, making them water soluble and allowing for excretion via urine, sweat and saliva production. While some may be fully metabolised, others may only be partially degraded, and some may be excreted without significant metabolisation. In all these cases, such drugs are often concentrated at centralised wastewater treatment plants (WWTPs) and subsequently released into waterbodies following improper or inadequate treatment; alternatively, they may end up in the environment more directly via combined sewage and stormwater systems following heavy precipitation events and overflow of raw sewage. We may also rid WW of drugs via sorption to solids at WWTPs, only for them to be reintroduced into groundwaters and other aquatic environments through application of sludge to farmlands or soil erosion (Jones et al., 2005).

Metabolites, as well as parent materials of these metabolites, should be understood to establish interactions between a plethora of organic pollutants and between organic and inorganic pollutants -e.g., pharmaceuticals and PPCPs or their metabolites with heavy metals and their organometals. An understanding of pathways into terrestrial and aquatic environment, both direct and indirect, and the processes through which bioavailability and the potential for bioaccumulation occur are vital to preventing these organic pollutants from entering the environment, as well as achieving proper treatment and removal from wastewater effluent to limit ecotoxicological consequences and allow for production of safe alternative fertilisers.

Unlike heavy metals, legislations pertaining to pharmaceuticals and restrictions on their use are far more difficult to achieve. After all, pharmaceuticals serve vital purposes in maintaining human and other animal health, particularly with extended human lifespans and following the publishing of the human genome in 2003, as well as the pharmaceutical industry being very financially lucrative, earning over 1.4 trillion dollars in 2022 revenue versus 390.2 in 2001 (Mikulic, 2023), and not exactly known for social or ethical responsibility –beyond the performative, that is.

Though much of the fear is blown far out of proportion, the fact remains that just between 2001-2020, 251 new drugs from 16 large pharmaceutical companies (Big Pharma) went to market following approval. To put this into perspective, this is nearly 50% of drugs of total drugs approved by the FDA (Zharonkov, 2023).

There are four dominant processes describing the fate of pharmaceuticals post ingestion by or administration to humans and other animals (Jones et al., 2005). First is *absorption* into the body, second is *distribution* throughout the body via the bloodstream, third is *degradation/detoxification/metabolisation;* whereby the parent drug is partially or fully degraded into its metabolites, and lastly *elimination/excretion* from the body –often in the form of urine, saliva or sweat. Pharmaceuticals of the same class may vary in persistence and metabolism. For example, despite both the depressants lorazepam (Ativan) and triazolam (Halcion) being in the class benzodiazepines, the former persists ≥24h and the latter only 6-8h (Jones et al., 2005).

There are various means of degradation occurring at WWTPs. These are: Biodegradation, photodegradation, deconjunction, partitioning and removal using sludge treatment. The bulk of biodegradation occurs during secondary treatment of wastewater, performed by aerobic and/or anaerobic microorganisms; with a fraction also occurring during transport to treatment plants. The ready biodegradability of pharmaceuticals varies significantly and the extent to which pharmaceuticals are degraded seems to depend on their molecular structure; with those containing long and branched side-chains being less biodegradable than those unbranched with short side-chains (Schwartzenbach, 2002). Unsaturated aliphatic compounds -in which carbon atoms are linked in open chains, are more biodegradable than aromatic compounds containing one or more aromatic rings (Jones et al., 2005) or those with more complex ring structures and sulphate or halogen groups.

In soils, some degradation occurs in the upper organic layers, decreasing down the soil column as mineral matter increases and organic matter decreases. Deconjunction, on the other hand, generally leads to increased excretion, especially in the case of steroid hormones as E. coli tends to produce more β-glucuridase enzyme. A higher amount of glucoronide and sulphate conjugates are likely to be excreted via this mechanism.

Between 2001 and 2010, there was a marked increase in literature pertaining to pharmaceuticals of emerging concern. This may be due to a few reasons: Public, scientific and governmental awareness increased and so the need and will to study and quantify these pollutants increased; and secondly, there were vast improvements in technologies used to detect these pharmaceuticals, e.g., gas chromatography-mass spectrometry and high performance liquid chromatography-mass spectrometry (Aus Der Beek et al., 2016).

Known PPCPs of concern and those of emerging concern (EC) are discussed below in terms of pathways into the environment, properties, metabolism and metabolites, ready biodegradability, as well as possible synergistic, antagonistic or additive toxicity potentiation in interactions between organic/organic compounds or substances and organic/inorganic compounds. Licit pharmaceuticals (e.g., antibiotics), licit psychoactive drugs (e.g., caffeine), medicinal psychoactive drugs of abuse (e.g., tramadol), and illicit psychoactive drugs (e.g., cocaine) will be discussed. There has been an influx of research published on such drugs prior to, during and following the Covid-19 pandemic (Verovšek et al., 2023; more refs), likely due to widespread monitoring of wastewater as a marker for the virus's prevalence on local and national scales. Regulation and detection of psychoactive drugs can be difficult due to consistent additions to the list as minor changes are made to molecules. Drugs are introduced to water and sewage as parent compounds and/or their metabolites. Whether licit or illicit, psychoactive drugs affect biota's behavioural and reproductive qualities and toxicity (Jin et al., 2022).

In a 2017 study by Archer et al. 90 emerging contaminants of concern (ECs) were examined and measured in influent to surface waters (55 ECs measured); effluent from (WWT or river outlets??)- 41 ECs; and environmental waters both up- and down-stream of WWTPs (40 ECs). The researchers found <50% removal of 28% examined ECs and <25% removal in 18% of examined ECs. Additionally, there were indications of back-transformation occurrence observed because of negative mass balance for some ECs. This may be due to aggregation of ECs followed by dissolution via biotic/abiotic processes, or the lack of metabolites and conjugate forms detection and subsequent deconjugation or back-transformation to parent compounds via the same processes (Archer et al., 2017).

Hormones are female (oestrogens), male (androgens) or gestational (progestogens) and most commonly occur in WW as natural and synthetic oestrogen. Oestrogens, progesterone, androgens, growth hormones and glucocorticoids have been measured in most coastal and surface waters around the globe, with high detection frequencies, and like other micropollutants occur in the (ng/L) range (Yazdan et al., 2022).

Natural oestrogen (estrone (E1), estradiol (E2), estriol (E3)) and synthetic ethynilestradiol (EE2) are commonly used powerful oestrogen and oral contraceptives showing persistence in surface water and fish – possibly leading to feminisation and infertility (Walker, 2012). Their persistence in fish may be caused by reabsorption by the liver. Toxicities of ethinynestradiol and other environmental oestrogens are additive. Natural oestrogen has a far shorter half-time (2-6 days) than synthetic EE2 (up to 46 days) and tend to both bind strongly with soil (Barel-Cohen, 2006). The natural hormone testosterone, on the other hand, can leach into the groundwater as it is not easily bound.

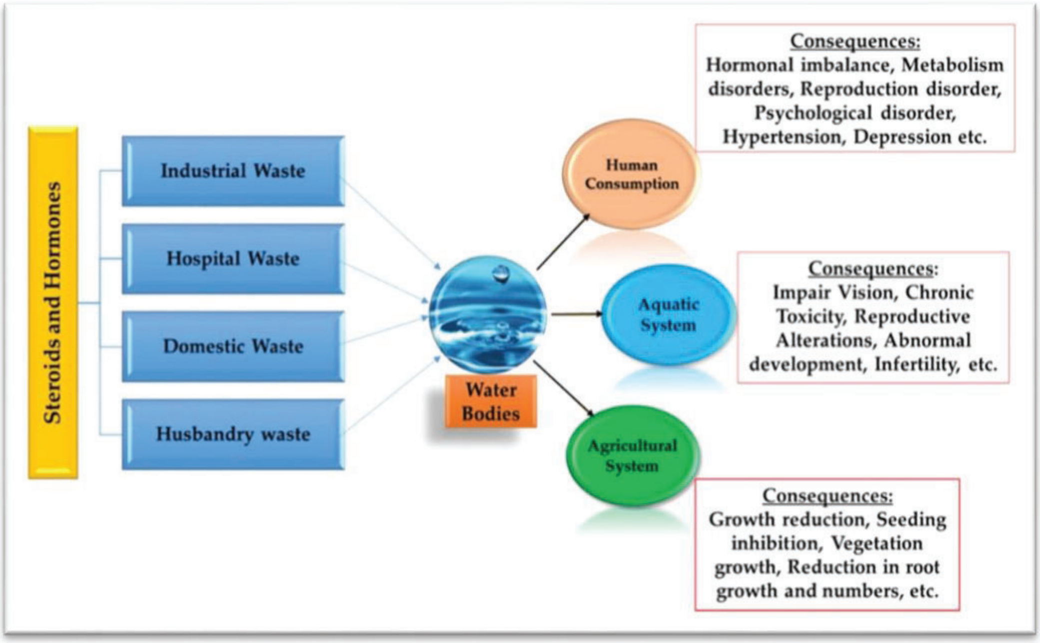


Figure 2: Dominant sources and impact of hormones and steroids on humans, aquatic and agricultural systems. Adapted from Yazdan et al. (2022).

There are three main methods used to rid WW of hormones and steroids at WWTPs. These are biodegradation, physical removal and chemical oxidation (Yazdan et al., 2022). Removal efficiencies can range from 10% up to 99%.

Some other compounds and metals can act as endogenous hormones disrupting the endocrine system of living organisms; these are known as endocrine disruptors (EDs). Brominated flame retardants (BFRs) and polychlorinated biphenyls (PCBs) (section X) used among other things as plasticiser and to reduce flammability of fabrics and electronics, per- and polyfluoroalkyl substances (PFAs) applied as water-repellent to textiles and pots and pans, and pesticides such as DDT, chlorpyrifos, atrazine and possibly glyphosate are all endocrine disruptors, as are the heavy metals Pb and Cd. Glyphosate is applied to nearly all maize grown as livestock fodder (field corn) in the US.

The first report investigating antibiotics routes of entry into the environment came in 1987 when dust from a pig fattening animal farm was studied retroactively, using dust collected over two decades -arising from the pigs, their excreta, feed and bedding. It found the antibiotics tylosin, chloramphenicol, tetracyclines and sulfamethazine in 90% of samples in quantities up to 12.5mg/kg dust (Hamscher et al., 2003).. Antibiotics in soils and waters can destabilise bacterial communities and services. Metabolites of sulfamethoxazole appear to be transformed by biotic/abiotic processes into their parent materials (Archer et al., 2017), reverting to their parent compounds via phytolytic mechanisms –through photon absorption in the visible and non-visible spectrum, while ciprofloxacin, ofloxacin, and metronidazole have been found to be non-degradable (Kummerer, 2000).

Diclofenac (brand name: Voltaren) is an organochlorine used as a non-steroidal anti-inflammatory drug which may cause poisoning (Walker et al., 2012). Secondary poisoning has been observed in India where the drug is commonly administered to and persists in cattle. This has led to population decline of predatory birds such as vultures feeding off dead cattle. Deconjunction of diclofenac metabolites is achieved by bacterial cultures (Archer et al., 2017). Furthermore, high concentrations of diclofenac have a direct effect on fish populations in terms of reduced fecundity and spawning (Walker et al., 2012).

The same effect is observed for ibuprofen and naproxen at concentrations of 100ng/L (Nesbitt, 2011), showing a decrease in egg fertilisation and subsequent potential decline in fish populations. Paracetamol and its metabolite salicylic acid display more biodegradability than many other pharmaceuticals (Jones, 2005).

The commonly used anti-inflammatory nonsteroidal drugs ibuprofen and diclofenac partially degrade given time when effluent is first treated using an aerobic biofilm reactor, in which most ibuprofen degradation occurs, followed by anoxic conditions, (Zwiener et al., 2000). Degradation may be delayed by the need for biofilm establishment. Sorption by sand filtration has been successfully used to completely rid wastewater of both ibuprofen and naproxen, another nonsteroidal anti-inflammatory drug Hua et al. (2003).

Antiepileptics are used in the treatment of epilepsy and as mood stabilisers in treatment of the mood disorders schizophrenia and bipolar. An externality of increased focus on mental health in both the global north and south due to reduced stigma could be an increase in concentrations of discharged pharmaceuticals used to treat a variety of psychiatric conditions.

X-Ray contrast media shows high persistence and potential for biotransformation into toxic products, as it may contribute to organic halogen compound load (Jones et al., 2005). X-Ray contrast media diatrizoate, iopamidol, iomeprol and iopromide have been reported to remain in the liquid phase at WWTPs and are rarely degraded or sorbed to solids (Jones et al., 2005). The first three show little to no biodegradation from raw to treated sewage. Studies have shown that iopromide is more readily photodegraded, with its products photodegrading further. Iopamidol, on the other hand exhibits some biodegradation in activated sludge at rates of 85% into two of its metabolites (Ibid, 2005). Remaining in the liquid phase should be considered to assure proper treatment and production of alternative fertiliser.

Psychoactive drugs affect the central nervous system by crossing the blood-brain barrier and impacting cognitive ability, mood, behaviour and risk assessment amongst others. They may also be used in management and treatment of psychoactive illness (Verovšek et al., 2023). Substances of plant origin tend to have antimicrobial properties; eg.opioids, cannabinoids, cocaine, nicotine and amphetamines. No research exists as of yet on the impact psychoactive substances have on algae; despite the possible cascading trophic effect up the food-chain.

Verovsek et al. (2023) found that nicotine, THC-COOH, amphetamines and cocaine residues had the highest removal efficieny from WWT effluent (>90%), both post activated sludge and membrane reactors, while treatment by moving biofilm membrane reactor (MMBR) showed lower efficacy in removal of cocaine and nicotine residues. In research conducted on 42 WWTPs in NE Spain examining nicotine (NCT) and its metabolite cotinine (COT), which may reduce oxidative stress and reaction to pain in the brain, high median values were found (32,000 ng/L and 5,100 ng/L respectively). In tap water in Spain, however, values were far lower, indicating possible degradation or removal of these compounds given time (Jin et al., 2022). Smoking significantly encourages Cd accumulation in the body as the heavy metal is well taken up by tobacco plants.

According to the United Nations Office on Drugs and Crime (UNODC, 2021-2025), there are about 52 million people using 30 forms of opioids in the world. Tramadol is a synthetic opioid used to relieve moderate to severe pain and, like all opioids, has a high potential for abuse and addiction. Toxicity of tramadol may occur by impacting serotonin production or uptake (serotonin overdose) and noradrenergic mechanisms, it can also cause brain injury at high doses (Puszkiel et al., 2022). Many primary and secondary metabolites of tramadol end up in WW due to fast metabolisation by the liver, with a mere 10-30% of parent material excreted from the body (Archer et al., 2017). Its recalcitrance is well established. In a study conducted on healthy Iranian biological male and female volunteers by Ardakani and Rouini (2007), exploring the pharmacokinetics of tramadol, one of three tramadol metabolites (*O,N*-didesmethyltramadol (M5)) showed a difference in AUC (Area under the curve) between biological males and females.

Tramadol tends to sorb to organic compounds resulting from sludge application to soil and organic constituents within the soil itself. This leads to higher bioavailability and accumulation, as the drug is sorped to solids or appears in microbial aggregates (Archer et al., 2017).

The UNODC estimates that there are 192 million yearly users of cannabis worldwide, be it medicinally for pain relief as well as a recreational illicit drug. Cannabis has become legal and better regulated in many U.S. states and in Canada, while it has been legal in Uruguay for years, and its use permitted in designated areas of Amsterdam in the Netherlands.

It would be beyond the scope of this thesis to detail every single licit and illicit drug, but it may suffice to say that they must all be considered when treating WW and recovering resources. Drugs are not going anywhere, but they are a direct indication of the intersectionality between the social, physical and natural sciences. Ignoring one discipline is ignoring all.

2.3.2 Micro- and nano-plastics

Microplastic particles (MPs; <5mm) have a known detrimental impact on aquatic environments. Following entry into aquatic systems, UV-radiation, chemical, physical and biological processes (Hwang et al., 2020; Manivannan et al., 2021) degrade MPs into macro- and nano-plastics (NPs) (± 100nm) allowing ingestion by “zooplankton, fishes, bivalves, mussels, nematodes and crustaceans” (Manivannan et al., 2021) and up the trophic scale. MPs and NPs may also exhibit toxicity to bacteria, making it difficult to use bacteria as ecotoxicological biomarkers; as they often are –e.g., indicators may either be increased bioluminescence from genetically modified bioluminescent (GMB) bacteria, or decreased luminescence (e.g., *Vibrio* *fischeri...)* when in contact with environmental contaminants (Manivannan et al., 2021). Additionally, UV irradiation expedites the degradation process producing NPs that are bioavailable via sorption by tissues and bioaccumulation of plastics leading to cell damage.

Microplastics may be *primary* or *secondary* (Hwang et al., 2020). While primary MPs exist in personal care products (PCPs) by design –e.g., toothpastes, facial and body scrubs etc., secondary microplastics result from degradation and fragmentation of anthropogenic plastic waste, and is the main source of plastic micro-, meso- and nano-particles found in both terrestrial (soils) and aquatic environments. The ingestion of these particles has been demonstrated in many marine organisms such as shellfish and fish, with particulate plastics found in 55% of studied organisms from markets in Indonesia and 67% in those from the USA (Rochman et al., 2015). Though secondary particulate plastic sources seem to cause the greatest damage, not PCPs, 75% of body exfoliants/scrubs contain these particles. If we put things into perspective: a "5mL average daily application of a facial exfoliant may contain somewhere between 4,594 – 94,500 MP particles" (Hwang et al., 2020 p. ; Napper et al., 2015) This indicates an important and continuous source of plastic pollutants into the environment. WWTPs do attempt to filter out and degrade microplastics using, for example, stabilisation ponds where particles may sediment and be bio- or photo-degraded, but their tiny size means much inevitably gets through filtration and is discharged into water bodies (Napper et al., 2015).

In addition to the effect such plastic particles have on biota, the high surface to volume ratio of microplastics and their potential sorbing of other environmental pollutants is high –leading to possible alteration in toxicity potential (Manivannan et al., 2021), possible potentiation and faulty measurements of contaminants.

About 20% of global plastics production goes into food packaging materials (Plastics Europe, 2022), as it can extend the shelf-life of food products significantly. It also allows large scale and intensive production and sale. Essentially, it fits into the yield and productivity focus within simplified traditional scientific agriculture. There has been great focus on *recycling* plastics and ensuring recyclability of plastics produced. In Europe in 2021, about 5.5 million tonnes of plastic were recycled and reintroduced to the market, a 20% increase from the previous year. This poses risks, however, as recycling entails known and unknown chemical migration of pollutants into foodstuffs, an example is recycled plastic beverage bottles made from polyethylene terephthalate (PET). According to the EU waste hierarchy, the focus ought to be on *reducing* the use of plastics and on their *reuse*; rather than recycling (EEA, 2019). UNEP is in the process of creating a Global Plastics Treaty which will be legally binding and aim to end plastics production (UNEP, 2022). There are fears of chronic human exposure to known and unknown hazardous chemicals in recycled plastics used in food packaging (Geueke et al., 2023). Especially alarming is the illegal recycling of plastic food packaging from recycled non-food-grade materials containing brominated flame retardants (BFRs), as well as recovery and reuse of secondary plastics waste where POPs may be present.

Though much research has been conducted on the impact of micropollutants in aquatic environments, little attention has been paid to that of presence in soils. There appears to be a direct correlation between soil

MPLs and GHG release contributing to climate change. The mechanisms remain unclear-as the research is limited, with some postulating impact on soil respiration or aeration, an altering of methanogen activity and an adherence to plant roots causing anoxic condition due to an abundance of carbon and nitrogen microbial gene sources within soils (Chia et al., 2023) as causes. Regardless, MP accumulation in soils is certainly a positive forcing on climate change.

In 2021, a group of researchers (Fujiwara et al.) from the Japanese Nara Institute of Science and Technology, discovered a bacterium capable of degrading highly durable and environmentally persistent poly(ethylene terephthalate) (PET) plastics via fermentation into poly(3-hydroxybutyrate) (PHB) -a biodegradable plastic and form of poly(hydroxyalkanoates) (PHA) due to the bacterium containing a PHA synthesis gene cluster. This bacterium is named *Ideonella sakaiensis 201-F6* after the city of Sakai, Osaka prefecture, Japan.

For nutrient recovery from sewage sludge, a method known as BioPOL has proven effective in efficiently removing contaminants (European commission, 2015). The method works by grinding sewage sludge to release biopolymers, a step followed by treatment with alkali salt (NaOH). This shows promise to reduce reliance upon petrochemical polymers as flocculants in treatment of sewage sludge, thereby reducing operational cost and environmental pollution caused by such polymers; particularly because 50% of Europe’s sewage biosolids are applied to agricultural lands, in addition to the great energy requirements for production of petrochemical polymers. Despite highly effective treatment methods at WWTPs for removal of such plastics, the large quantities of sewage produced and treated lead to high levels present in discharged effluent. An issue which may arise from the application of BioPOL is that resulting organo-minerals may not be in a form compatible with commonly used agricultural equipment (European commission, 2015). This shows promise for reduced reliance upon petrochemical polymers as flocculants in treatment of sewage sludge, thereby reducing operational cost and environmental pollution caused by such polymers; particularly because 50% of Europe’s sewage biosolids are applied to agricultural lands, in addition to the great energy requirements for production of petrochemical polymers. Despite highly effective treatment methods at WWTPs for removal of such plastics, the large quantities of sewage produced and treated lead to high levels present in discharged effluent. An issue which may arise from the application of BioPOL is that resulting organo-minerals may not be in a form compatible with commonly used agricultural equipment (European commission, 2015).

2.3.3 Persistent organic pollutants (POPs)

POPs are semi-volatile, man-made, polyhydrogenated hydrocarbons containing bromine, chlorine or fluorine. They persist, bioaccumulate and biomagnify due to their lipophilicity and low water solubility and are neither metabolised nor excreted; they are the most dangerous compounds synthesized by humans. Their lipophilicity allows them to biomagnify up the trophic scale in fatty tissues of humans and other animals, leading to cancer and autoimmune diseases, impact on fecundity (e.g., lowering of sperm count) and neurodevelopmental issues amongst others. Omnivores and carnivores are at greater risk of exposure and bioaccumulation, though inhalation and skin absorption of aerosols are also pathways of exposure. Common POPs come from industrial chemicals, pesticides and arise as byproducts of waste incineration or other industrial processes.

Due to volatilisation, poor degradation and long half-lives t1/2, they persist for years or decades in the environment, while being transported through the atmosphere and aquatic environments due to high motility (Arp and Hale, 2022). They may also cover long distances and end up far from their original source or area of application; making national or local regulation insufficient. The Stockholm convention on persistent organic pollutants, organised and mediated by the United Nations Environmental Programme (UNEP), and aimed at phasing out and regulating the use and production of POPs at an international level, was therefore signed in 2001. First, what came to be known as the *Dirty dozen* were targeted. These were divided into three categories: Pesticides (aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex and toxaphene); Industrial chemicals (PCBs); and Unintended by-products (dioxins and furans). Despite DDT being on the list, the convention specifically allows its use in combating Malaria mosquito vectors indoors. In 2009, 9 additional POPs were added to the list and by 2010 there were 174 parties and 151 signatories to the convention. Since then, other POPs have been added to the list or recommended for addition.

Despite low background concentrations, their ubiquity and long-term exposure poses known and proven risks to biota, due to chronic exposure and persistence. Exposure may even occur prenatally through maternal fat deposits and postnatally through breast milk ingestion and impact may appear later in life; making it more difficult to identify the role POP exposure poses in the longer term.

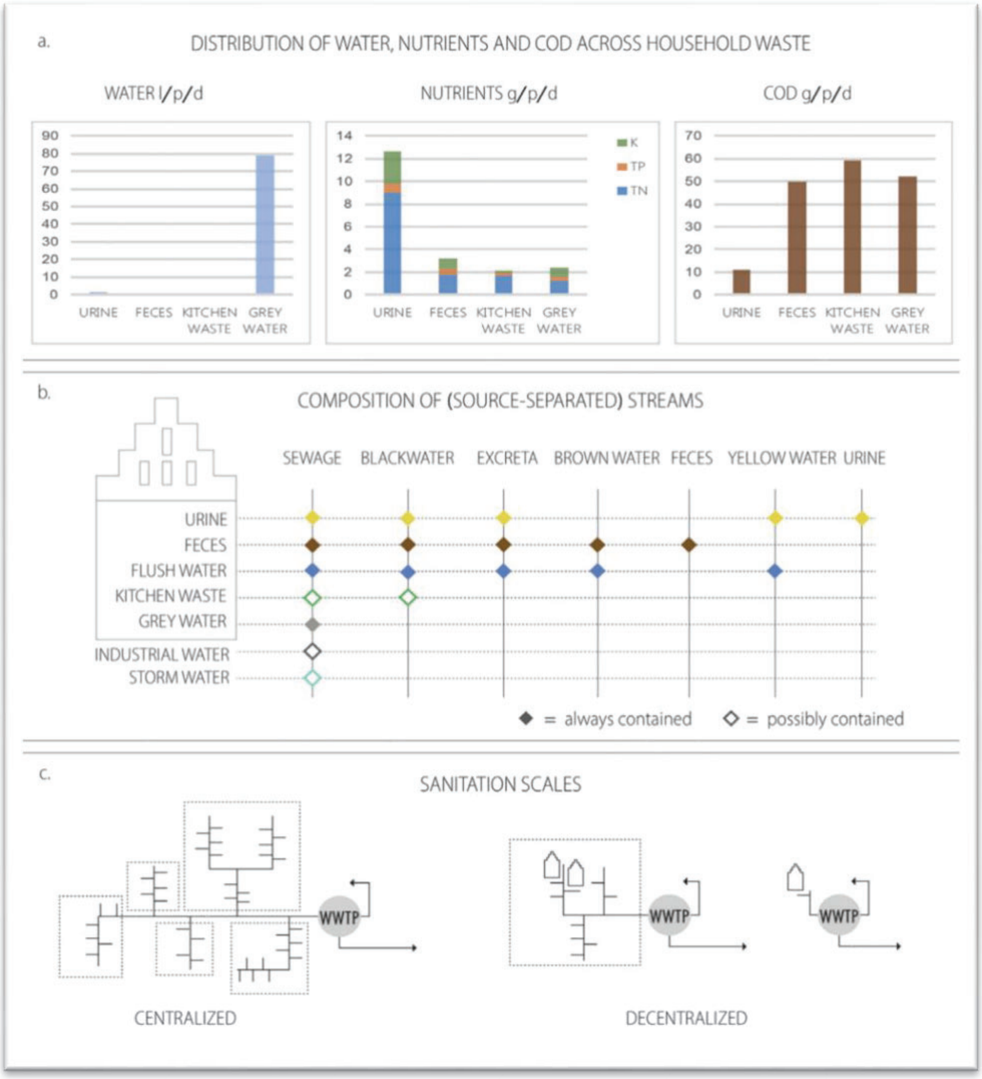
PCBs have well known links to neurological disorders and are endocrine disruptors. They are used as flame retardants, plasticisers, for caulking, adhesive, coolant and in contactless copy paper amongst other applications. Over 90% of dl-PCB and dioxins in humans come from foodstuffs of animal origin, with highest accumulation in fatty meats.

3 Resource recovery

On average, a human will excrete 500L of urine per year, and this fraction of excreta contains the bulk of macronutrients needed for plant growth (80-90% of N; 50-80% of P; 80-90% of K) (Kemacheevakul et al., 2014; Gunnarsson et al., 2023). These values differ based on individual nutrition/diet and water usage in conventional sanitation. Most of urine is made up of water (95%) and <1% N. This is diluted further using flush toilets, and due to mixing with faeces and greywater results in pollution of generally sterile urine, which tends to contain low concentrations of heavy metals. This is an argument in favour of urine diversion, discussed in Section 3.3. A human will excrete approximately 4kg N, 0.5kg P, 1kg K and 539kg water

(H2O) (Vinnnerås et al., 2006). No more than 1% of domestic wastewater is made up of urine, yet this fraction contains 80% of N and 50% of P present in domestic wastewater. When urine is excreted, the non-volatile N in the form of urea undergoes enzyme hydrolysis producing the GHG NH3, which means that both storage and application will require consideration.

Though urine is by far the most valuable domestic waste resource in terms of fertiliser production, faeces and kitchen waste are of value for production of soil amendment products, as well as energy. Greywater, sourced from sink and shower water may also be reused after treatment.



3.1 Urine diverting dry toilet (UDDT)

Urine diversion separates (diverts away) urine from faeces using specialised toilets with two sections: a front section for collection of urine and a rear section for collection of faeces and toilet paper (into separate ventilated compartments. Faeces may be sent to a centralised WWTP through traditional “flush and forget” sanitation or treated locally via composting, anaerobic digestion for biogas production or other methods. Urine diverting toilets in general may include the addition of water (be it to faeces or urine) but must all separate the waste fractions. This separation enables collection of wastewater fraction containing the bulk of nutrients and least pathogens and impurities, namely urine. Opting for urine diverting dry toilets (UDDT), which do not use water, can reduce odour and exposure to flies as well as avoid the need for collection of sensorily unpleasant faecal sludge (SSWM – Urine diversion components). An important consideration is proper design to prevent or limit cross-contamination, as faeces can introduce enteric pathogens such as enterococci, helminths, salmonella and ascaris amongst others into generally safe urine and requiring additional treatment (Devkota et al., 2019). Cleaning is also made more difficult if cross-contamination occurs and blockages are made more likely. Also important is proper design of pipes in terms of slope and diameter to allow easy and unobstructed transport of urine into collection chambers, which may otherwise give off odour or freeze during winter. Blockages may also be due to Mg and Ca salts precipitation (e.g. struvite) which can in milder cases be dealt with using mild acids and hot water, and in more severe cases using stronger acids (>24% acetic acid) or baking soda (Devkota et al., 2019).

UDDTs always contain separate urine and faeces tanks/chambers but may contain a single chamber for faeces -a system which can also be portable, or a double chamber (Devkota et al., 2019); all of which may be modified for sitting or squatting. An alternative to immobile tanks is removable containers. It is important to account for the large volume of urine produced, compared with faeces produced, when dimensioning tanks in order to avoid overflow. After defecation, as these systems do not use water, those practicing washing as opposed to wiping require separate drainage preventing water from reaching the faecal compartment. Drying agents such as wood ash are added.

A challenge with storage of urine is the fast-paced hydrolysis of urea, allowing nitrogen to be lost in the form of ammonia gas due to increase in pH (SIEUGreen D2.4). Additionally, transportation costs may be high due to the high percentage of water used in conventional sanitation. Strategies for the concentration of urine to reduce cost as well as N stabilisation for nutrient recovery are discussed in section 3.3.

Urine diversion may be followed by dry composting, a biological process whereby aerobic microorganisms rapidly break down organic matter producing energy in the form of heat. This distinguishes the process from anaerobic degradation, which is slow and tends to keep a significant amount of carbon bound as CH4 which can be combusted as biogas.

3.2 Biogas sanitation - Anaerobic digestion

Anaerobic digestion (AD), an old wastewater treatment technology developed and described in Mumbai, India as early as 1859 (Vögeli et al., 2014), relies on anaerobic bacteria performing decomposition services at various ideal temperatures: thermophilic and mesophilic. It consists of the four sequential steps hydrolysis, acidogenesis, acetogenesis and methanogenesis (Moges et al., 2020). Anaerobic microbial activity, without free oxygen available, degrades organic matter to methane (CH_4), carbon dioxide (CO_2), hydrogen (H), nitrogen gas (N_2) and trace amounts of hydrogen sulphide (H_2S) (SSWM). AD efficiently removes (C) while producing biogas -the primary constituent of which is CH4 and biomass; producing effluent poor in organic carbon (OC) yet rich in orthophosphate (PO_4^{3-})-P and ammonium (NH4+)-N - essentially producing nutrient rich digestate. Disruption, or even halting, of AD may also occur due to the great variety of waste content, as well as inhibiting substances. Such inhibitors include heavy metals, ionised “non heavy" metals, ammonia (NH3) and sulphide (S_{2-}). Aerobic degradation (in the presence of free O2), which occurs very rapidly due to the short reproductive cycles of aerobic microorganisms and releases energy in the form of heat (temperatures may reach 70C in compost heaps) is less affected by the presence of these substances, but also not suitable for biogas production. AD microorganisms, on the other hand, have longer reproductive cycles and are unable to degrade an equal amount of OM rapidly into heat, meaning energy remains in the form of CH4 biogas to be used as biogas (Vögeli et al., 2014). Temperature in the biogas reactor can for example affect the end quality of digestate in terms of pollutant removal.

Traditionally AD was only used to treat liquid waste, such as manure or sludge. In the 60s more attention was paid to the great biogas production potential of solid waste; the organic dry matter fraction of which is termed volatile solids (VS) and ought to make up >70% of total solids as the constituent available for biogas production (Vögeli et al., 2014). There are various forms of AD: wet or dry, continuous or batch and single- or multi-stage systems. Some 90% of P precipitates out of sewage sludge in anaerobic digestion, and recovery in the form of struvite has been found to be possible at rates of 20-30% (European commission, 2015).

The production of biogas from solid waste products provides alternatives to wood and charcoal burning in low-income nations and communities, as well as preventing deforestation. In Sub-Saharan Africa, the dominant source of wood-smoke exposure in rural communities is domestic cooking, in addition to occupational exposure (e.g., charcoal production and bakery). Results of such exposure are *“respiratory diseases including acute respiratory illness and impaired lung function .... increased blood pressure, low birth weight, oesophageal cancer, sick building syndrome, non-syndromic cleft lip and/or cleft palate and under-five mortality”* (Bede-Ojimadu and Orisakwe, 2020, p.1). Gender plays a role. One of the main determinants for exposure and health risk is quite simply being biologically female and performing socially constructed gender roles.

In cities where fossil fuel is the more common source of energy, there is a certain supply risk and reliance on market price fluctuations; more reliable and renewable sources would be of value (Vögeli et al., 2014). Additionally, AD can curtail CH4 emissions into the environment and their subsequent impact as a positive forcing on climate change Though carbon dioxide (CO2) has a much longer atmospheric lifetime; >100 years versus 12 years for methane, CH4 absorbs ca. 25x the amount of radiation C does. AD is also of value in remediation efforts on depleted arable lands which have been farmed intensively and conventionally; via nutrient-rich digestate application.

Throughout Asia, many countries have installed biogas systems in the thousands or millions (e.g., 225,000 in Nepal by 2011; 100,000 in Vietnam by 2010; 4 million in India by 2014 and 40 million in China by 2011 (Vögeli et al., 2014)).

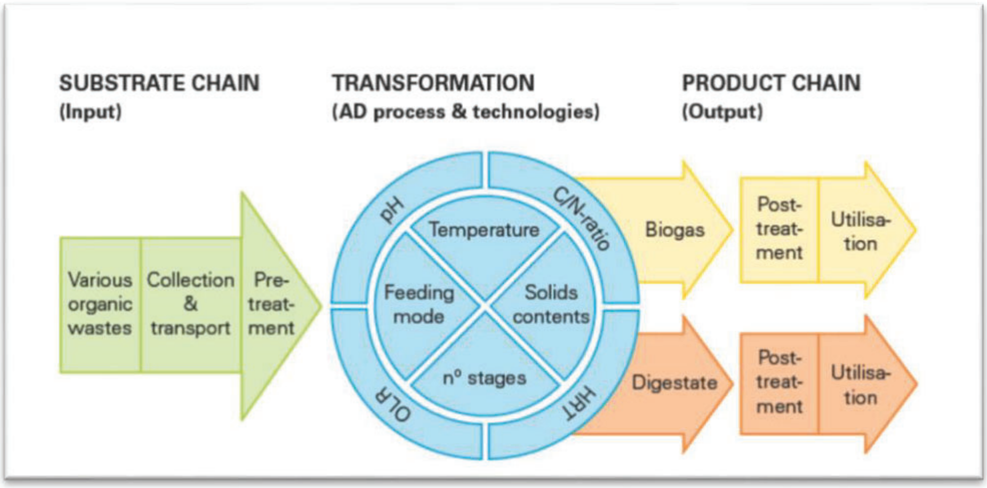


Figure 3: Process chain of anaerobic digestion. Adapted from Vögeli et al., 2014. HRT: hydraulic retention time; OLR: organic loading rate.

In Norway, surprisingly, the antibiotics penicillin G and amoxicillin have been detected at concentrations ranging from 460–960 µg kg^{-1} dry weight in biogas digestate from food waste and manure (Nesse et al., 2022). This may serve as a reminder that whether one is in the global south or north, one ought to think the same: reduce, remove, recycle.

3.2.1 Resource recovery of co-digested excreta and organic household waste, Lesotho

Between 2002 and 2010, 140 anaerobic fixed dome biogas digestors with a compensation chamber were constructed in landlocked Lesotho by Technologies for Innovation (TED) on a purely demand-driven basis (Vögeli et al., 2014). Fixed dome digesters have a gas-tight dome which can be constructed from various readily available materials such as plaster, bricks or concrete.

Drinking water for the nation’s capital is sourced from a catchment area surrounded by pit latrines, and water is scarce (Lebofa, 2021). Additionally, very few households are connected to the city’s centralised WWTP, meaning septic tanks are mostly used, which requires costly emptying every year while few cesspool emptiers are available relative to demand. The goal of these projects is the production of gas for cooking and water boiling, water for fertilizer and the production of soil amendment products. Additionally, there is a need for job generation, as well as regeneration of soils depleted by overgrazing in a nation suffering drought, water scarcity and deforestation.

Compensation chambers are used to minimise pressure within the main chamber of anaerobic digesters when biogas is produced, whereby the pressure displaces sludge which is emptied via a pipe and sent to a storage tank exposed. The storage tank ought to be equal to the volume of biogas in the main chamber. This also minimises losses due to overpressure. The systems contain three main components: A *digester*, an *anaerobic baffled reactor* (ABR) filled with shredded plastic bottles providing surface areas for bacteria to grow, where effluent passes through multiple consecutive compartments in which particles settle and come in contact with bacteria containing sludge, and a *planted gravel filter* (PGF) in which water plants may be grown (Figure 4). TED uses pumice discarded by the textile industry as media in their PGFs, further increasing the circularity of their systems. Nutrient-rich effluent is then stored in a tank, to be collected in buckets, pumped, or used to irrigate using gravity (Lebofa, 2021). Units are fed predominantly with black and greywater from individual households and small communities, sometimes supplemented with agricultural waste and/or animal manure; while some were fed exclusively with manure- in these cases biogas production was higher (Vögeli et al., 2014). As opposed to higher biogas production occurring from addition of animal manure, the addition of agricultural waste reduced the digestors' efficacy, due to system overload and marked increase in chemical oxygen demand (COD). A positive correlation has been observed between pressure increase due to increased storage time and leakage of gas, be it from escaping or automatic pressure release (Ibid).

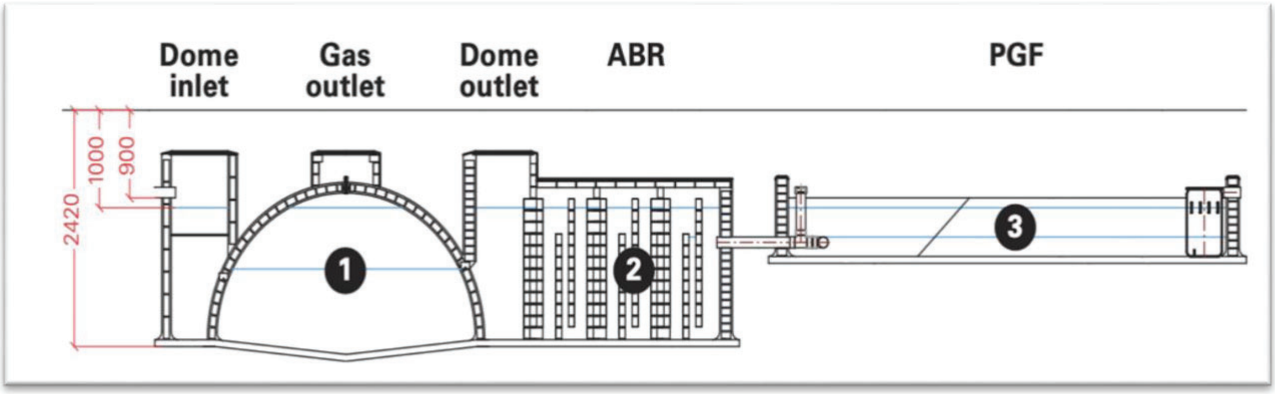


Figure 4: DEWATS-Biogas-System of TED-BORDA comprised of three stages left to right: Anaerobic fixed dome biogas digester, an anaerobic baffled reactor (ABR) and finally, a -horizonal flow- planted -graded- gravel filter (PGF) which can be aerobic and/or anaerobic. Adapted from Vögeli et al. (2014).

3.3 Urine

As mentioned in section X, a prohibitive factor in the recovery of nutrients contained within urine when mixed with water is transportation cost (weighs more), as 97% is made up of water, and distance between the source (e.g. a city) and area of application (e.g. farmlands outside the city). To reduce cost and required storage space during transport, urine may be diverted (see section X), collected and concentrated by extracting nutrients and/or removing water; producing a nutrient rich extract. Additionally, the volatilisation of urea in urine following excretion means much valuable N is lost. Stabilising urea and preventing hydrolysis catalysed by urease into ammonia by raising pH and temperature can help limit losses while recovering resources and concentrating urine. While synthetic urea fertiliser has an N concentration of 46%, that in urine is 0.6% (Vinnerås et al., 2006). It is therefore beneficial to concentrate urine to maximise nutrient extraction and transport efficiency, particularly if there is 40-50km or longer from the collection to the application point (Jenssen and Refsgaard, 1998).

Strategies for concentration of urine tend to focus on one or the other: remove water or extract nutrients, while one combines the two. A shortcoming of the first strategy is loss of nutrients and of the second is liquid effluent production that must be dealt with, and which may require further treatment before discharge. Prevention of N loss can be achieved by lowering pH via the use of acid or by nitrification of NH3, or by raising pH and temperature to stop enzyme hydrolysis. Some urine concentration and N stabilisation strategies are discussed below.

3.3.1 Water removal

Many technologies for urine concentration through water removal exist. Examples are passive evaporation, membrane distillation and forward osmosis (Simha et al., 2020). It is however nitrification-distillation which allows for recovery of all the nutrients in urine, especially nitrogen.

Nitrification –distillation produces a nutrient rich liquid concentrate. Diverted urine is first stored and pumped into a nitrification column to stabilise N in the urine. It is then vacuum distilled to rid it of water (Gunnarsson et al., 2023). It is common to filter using activated carbon between the two steps to maximise contaminant reduction, as is the case in production of the alternative fertiliser Aurine discussed further down in this section.

One matter of concern with the process of nitrification-distillation in the production urine fertiliser is the emission of N2O (Section X). N2O emissions can account for 45% of the process' C-footprint (Faust et al., 2022). A highly effective method to curtail these emissions are reduction of storage time between the step of nitrification and GAC filtration; a reduction of up to 100% is possible. A 60% reduction in emissions can be achieved by maintaining NO2- concentrations below 5mg/L and avoiding anoxic conditions. The use of alternative energy sources can also reduce C-footprint by 85%. Microwave pyrolysis (described at the end of this section) and CH4 produced via biogas digestion are possible sources of such energy.

3.3.2 Nutrient extraction

Extraction of nutrients may be performed via stripping, ion exchange, adsorption and precipitation (Simha et al., 2020). Ion exchange can be followed by a struvite precipitation step allowing for the recovery of P in the form of a slow release, crystalline phosphate fertiliser, as well as K or Ca if their ions are used instead of the commonly used Mg ions.

Ion exchange with struvite precipitation recovers nitrogen using ion-exchange and phosphorous using struvite precipitation. Diverted urine is stored to prevent volatilisation into ammonia (NH3), then urea hydrolysis produced ammonium (NH4+) is sent through an ion-exchanger and sorbed to negatively charged resin (Gunnarsson et al., 2023). Struvite is commonly precipitated by adding Mg-ions and separated by filtering.

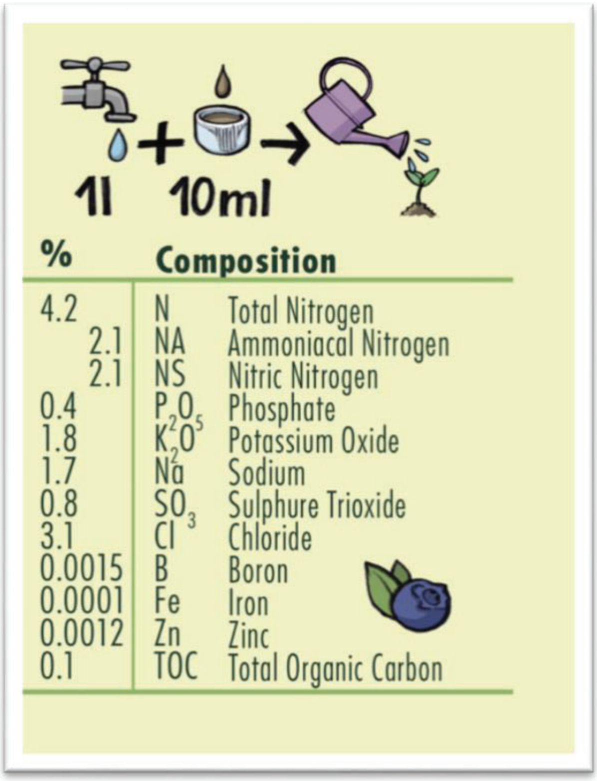
3.3.3 Combination of water removal and nutrient extraction

Alkaline dehydration may be used to treat diverted urine at household, semi-centralised and centralised levels by transforming urine into a dry powder (or a liquid concentrate) using an alkaline medium at pH >10 to prevent urea (CO(NH2)2) hydrolysis and N loss and then dehumidifying (Gunnarsson et al., 2023). This method combines the two strategies: water removal and nutrient extraction. Since urea present in urine is highly volatile once excreted, dehydration on its own is not a possible strategy for production of urine fertiliser. Following excretion, the enzymes urease catalyse hydrolysis of urea into NH3, followed by additional NH3+ release due to spontaneous hydrolysis of carbamate (H2N COOH) into carbonic acid (H2CO3) (Senecal and Vinnerås, 2017). Even when diverting urine, there remains a chance for some contamination from the plentiful urease-forming bacteria present in faeces which may further contribute to enzymatic hydrolysis; forming biofilm on pipes transporting urine into storage tanks (Vinnerås, 2002).

To do this at a centralised level, a limebox containing magnesium oxide (MgO) can be installed in the UD toilet to avoid N-loss (Gunnarsson et al., 2023). Alkaline dehydration of urine is a viable alternative to mineral fertiliser and conventional WWT, contributing to reduced eutrophication, GHG emissions and water consumption. NH3+ volatilisation with subsequent acidification and particulate matter emissions, as well as energy requirements are some possible bottlenecks Martin et al. (2023). Other alkalising agents may also be used, such as wood ash and calcium hydroxide (Ca(OH)2). Simha et al. (2020) have found that when using these two alkalising agents separately and in conjunction with the drying media substrates wheat bran, biochar and desert soil >90% of N could be recovered at a temperature of 60°C.

The addition of an alkaline agent, such as wood ash, raises pH. As urease enzyme activity is limited by pH and temperature, non-enzymatic hydrolysis still occurs but at a far slower rate (10^10 slower) compared to enzyme catalysed hydrolysis (Senecal and Vinnerås, 2017). Wood ash has a high pH (>12.5) and a large surface area, both facilitating alkalisation and dehydration of urine.

In 2018, following a testing phase beginning in 2015, the Swiss Federal Office for Agriculture became the first in the world to approve the use of fertiliser sourced from human urine, developed by VUNA for application to all plants, including crops for consumption (Keogh, 2018). Following source separation (UD) the production process consists of nitrification and treatment with activated carbon, followed by distillation.



%	Composition	
4.2	N	Total Nitrogen
2.1	NA	Ammoniacal Nitrogen
2.1	NS	Nitric Nitrogen
0.4	P_2O_5	Phosphate
1.8	K_2O	Potassium Oxide
1.7	Na	Sodium
0.8	SO_3	Sulphure Trioxide
3.1	Cl	Chloride
0.0015	B	Boron
0.0001	Fe	Iron
0.0012	Zn	Zinc
0.1	TOC	Total Organic Carbon

Figure 5: Composition of 10ml Aurin diluted in 1L water (Vuna)

3.4 Algae biofertiliser

Microalgae are ubiquitous photosynthesizing unicellular organisms encompassing an enormous number of species, with estimates ranging from 1-10 million. These organisms are highly efficient photosynthesisers and reproduce via cellular division, allowing for swift reproduction and short life cycles. Microalgae are mostly applied to soils as biofertilisers, but are also used as biostimulants and biopesticides (Section X). All of these applications contribute to plant growth and soil remediation efforts.

There are three forms of algae bio-fertiliser, these are: live cyanobacteria, foliar fertiliser and slow-release fertiliser (Lu and Xiao, 2022). Microalgae can be grown while using wastewater as growth media (Barros et al., 2015), thus constituting a nutrient-rich source of bio-fertiliser which may be grown in fresh, brackish and saline water alike. Such fertiliser can enrich soils with both macro- (NPK) and micronutrients (Ca, Fe and Mg) (Anand et al., 2023). Additionally, an array of other products may be produced; due to microalgae accumulation of valuable compounds such as lipids, proteins, carbohydrates and pigments; such as pharmaceuticals, nutritional supplements and biofuels while increasing sequestration of CO2. Pharmaceutical products include anticarcinogens and antibacterials; in the case of antibacterials, healthy algae exposed to little contamination tend to produce these substances, while those exposed to stressors such as heavy metals experience higher rates of harmful bacterial development (Anand et al., 2023). This further underlines the need for proper pretreatment of growth media sourced from wastewater.

The symbiotic relationship between algae and bacteria is important, as healthy algae tend to form "consortiums" with bacteria, as well as cell-to-cell contact with other algae (Figure 6). When stressed, colonisation by harmful bacteria is encouraged and these consortiums are destroyed, reducing algae's efficacy in ridding wastewater of toxic pollutants (Ibid, 2023).

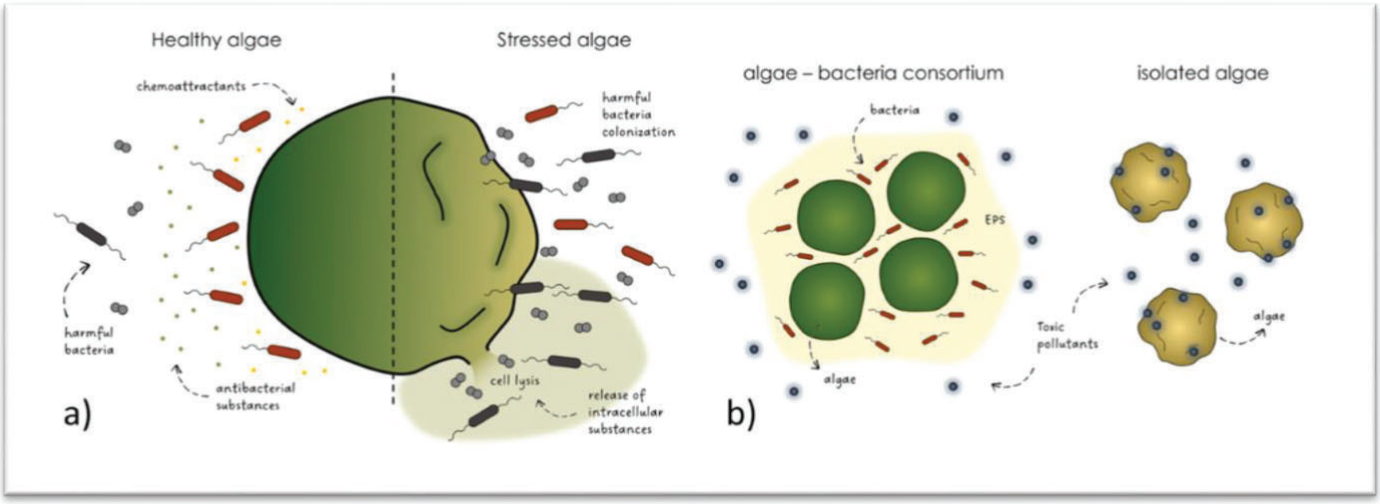
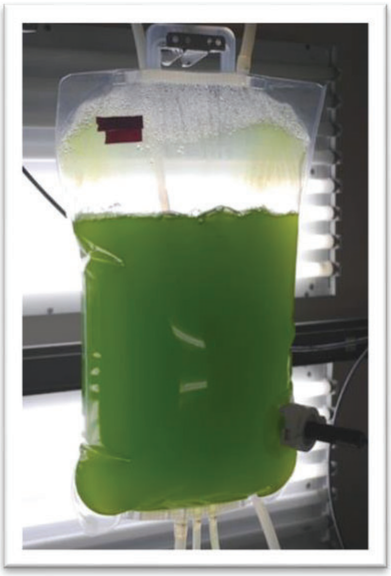


Figure 6:. The impact of environmental and toxic pollutant stressors on algae-bacteria consortiums (a) and cell-to-cell adhesion (b) (Anand et al., 2023*)*

Microalgae may be grown in open or closed systems. While open systems such as ponds are cheaper and easier to construct and operate, they are vulnerable to contamination, evaporation and weather patterns. Closed systems allow us to exert more control over environmental conditions such as light, temperature, pH and nutrient influx, while being up to 3 times as productive as open systems (in terms of biomass), despite being more costly. These most used and simple closed systems are *tubular (horisontal or vertical)*, *flat panel* and *plastic bag photobioreactors* (Image 1). The design of a photobioreactor is an important consideration. Square systems may, for example, be more susceptible to the development of unproductive "dead zones" (Fuchs et al., 2021)



Images 1: Top left: Tubular (vertical) photobioreactor (); Top right: Flat panel photobioreactor (Ruhr universitat Bochum); Bottom: Plastic bag photobioreactor (Cellana)

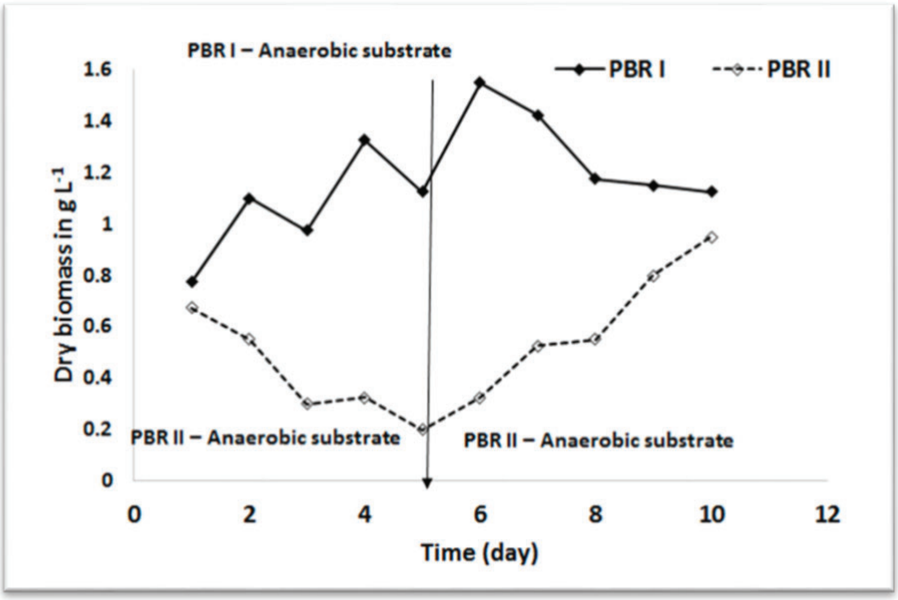
Atypical systems have been developed to effectivise and hygienise the process (Leong et al., 2023). The flat-panel airlift photobioreactor is six times less costly than the traditional flat-panel system (Fuchs et al., 2021). Due to high illumination to volume ratio, flat-panel airlift systems, alongside horisontal tubular photobioreactors show the most promise in terms of microalgae production on a large scale (Images X).

Produced microalgae must first be extracted from growth media and then dehydrated quickly to avoid deterioration of harvested product. Extraction can be achieved in several ways, while dehydration has three commonly used methods. The most cost-effective of harvesting methods is *flotation*, which allows algae to float on the media surface by adding microbubbles of air to growth media, enabling harvesting without needing chemicals. By addition of cationic polymers and multivalent cations, *flocculation* is achieved, effectively neutralising algae charge. Microalgae have negatively charged surfaces as they contain algogenic organic matter (AOM), making their aggregation/coagulation an issue in the production of algal bio-fertiliser, as well as in WWT more. *Centrifuging* is a highly efficient and quick method which may damage the harvested algae and is energy intensive, while *filtration* is achieved using semipermeable membranes in three possible ways: ordinary, microfiltration (0.1 to 10 μm) and ultrasonic filtration.

Sun drying relying on solar energy, *spray drying* by exposing algae in the form of mist to consistently heated air and *freeze drying* via sublimation are commonly utilised dehydration strategies (Ammar et al., 2022). The least costly method is sun drying but is highly climate dependant.

In AD effluent, OC levels are low, which reduces denitrification and thereby N recovery. On the other hand, nutrient content in the effluent is high. This high N content may inhibit algae growth due to nitrification of NH4+ to NO2-. Additionally, low micronutrient values of particularly Mg can reduce productivity; meaning supplementation may be necessary (Moges et al., 2020).

In production of biofertiliser from the algae Chlorella Sorokiniana, substrate from AD effluent kept under anaerobic conditions can produce more biomass when compared with that kept under aerobic conditions for part of the treatment, followed by anaerobic conditions. A steady decline in biomass has been observed during the aerobic stage whereas biomass increases steadily under anaerobic conditions before stabilising. (Scatter plot 1). This likely corresponds to nitrification of $NH4+$ in substrate to $NO2-$, as nitrite is toxic to the algae; inhibiting production. Multiple strategies are possible for circumventing the nitrification effect, such as nitrification to $NO3-$, reduction of storage time and maintaining anaerobic conditions in the feeding tank (Moges et al., 2020).



Scatter plot 1: *Biomass production of Chlorella Sorokiniana from substrate under consistently anaerobic conditions (PBRII) and aerobic followed by anaerobic conditions (PBRI). (Moges et al., 2020).*

3.5 Struvite

Struvite, or magnesium ammonium phosphate ($MgNH4PO4·6H2O$), is a white, crystalline, orthophosphate mineral with a solubility constant of 10^−13.26 in water (Ohlinger et al., 1998). This solubility constant is increased at lower pH (Shih and Yan, 2016) - e.g., 0.033 g/100ml in 0.001M HCl and 0.178 g/100ml in 0.01M HCl at 25°C (Le Corre et al., 2009). Precipitation of magnesium (Mg^{2+}), ammonium (NH_4^{+}) and phosphate ($PO4^{3-}$) occurs in equal stoichiometric ratios (1:1:1 -Mg:N:P) with increased alkalinity (often pH is adjusted to 9 for precipitation to occur (SiEUGreen ref) when their concentrations surpass the solubility constant (Shih and Yan, 2016). PH is often adjusted using $Na(OH)2$.

Fresh urine has pH in the range of 5.6-6.8 (Kemacheevakul et al., 2014), and when urea is hydrolysed (in the presence of the catalyst urease) producing ammonium and bicarbonate, pH increases leading to struvite supersaturation through increased $PO4^{3-}$ concentration (Wilsenach et al., 2007). Following storage of urine, for example, urease activity is heavily reduced once pH has increased and stabilised due to faster die-off of urea-hydrolysing bacteria in alkaline solutions (Kemacheevakul et al., 2014). The precipitation of K-struvite ($MgKPO_4 \cdot 6H_2O$), an analogue to Mg-struvite, enables the recovery of both potassium (K) and $PO4^{3-}$ from wastewater. Potassium is another limited resource, commonly mined from potash. Additionally, other forms of precipitated phosphate salt which are struvite-like can occur, such as calcium phosphates (e.g. Calcium ammonium phosphate ($CaNH_4PO_4.7H_20$)) or other magnesium phosphates (e.g. dittmarite ($MgNH_4PO_4 \cdot H_2O$)) ((EU) 2019/1009 STRUBIAS). As such phosphate salts do not necessarily occur in true and rigid crystalline structures due to impurities, their production process is better described as one of "precipitation" rather than the "crystallisation" of MgNH4PO4·6H2O.

During anaerobic treatment of wastewater, $MgNH_4PO_4 \cdot 6H_2O$ commonly precipitates due to increased alkalinity, leading to maintenance issues such as formation of scale in pipes. The main precipitation parameters are temperature, pH, molar ratios, supersaturation and the presence of foreign ions and their cation competitiveness (e.g. calcium ($Ca+$) or magnesium ($Mg+$) (Bouropoulos and Koutsoukos, 2000; Muryanto, 2017; The removal and reuse of (NH_4^+ -N) and ($PO4^{3-}$), plant available forms of N and P, is made possible through struvite precipitation. Mg^{2+} ions are most commonly added to aid in precipitation, most efficiently in the form of $MgCl_2 \cdot 6H_2O$, another form being $Mg(OH)_2$ (Uludag-Demirer et al., 2005).

A significant amount of research has been conducted on struvite. Sludge, human urine and anaerobic digestion make up the bulk of studied wastewater resources and treatments (Li et al., 2019).

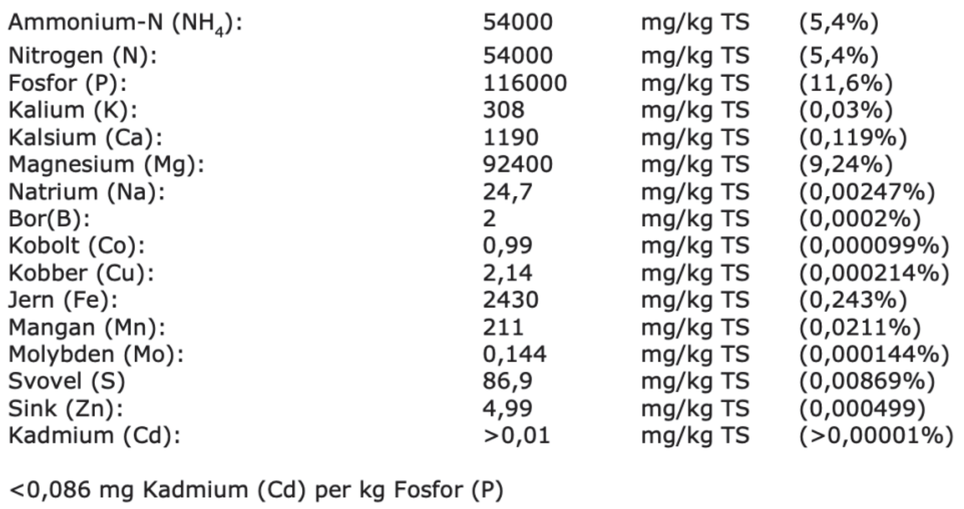
In struvite precipitated from urine, values on uptake of pharmaceuticals and heavy metals per gram $PO4^{3-}$ and NH_4^+ in struvite precipitated from human urine have been measured at concentrations far lower than those observed in most commercially available fertilisers (Ronteltap et al., 2017). Pharmaceuticals and hormones spiked into urine rarely precipitate out of solution, and struvite from non-spiked urine does not register significant concentrations. The reaction half-life was seven days for cadmium (Cd), copper (Cu) and lead (Pb), which most often precipitated spontaneously in urine and therefore often appears at higher concentration rates. Concentrations generally remained lower than those in commercial fertilisers, for both Cd and Pb, as well as studied metals which do not precipitate spontaneously: arsenic (As), chromium (Cr), cobalt (Co), nickel (Ni), zinc (Zn), aluminium (Al) and iron (Fe).

In research conducted by Kemacheevakul et al. (2014) on storage times of urine (human and synthetic) used in struvite production with spontaneous precipitation and struvite crystallisation, ideal retention time for phosphate recovery was found to be 5 days, at which time approximately 70% of P was recovered from both human and synthetic urine. As previously mentioned, the half-life for precipitation of metals studied by Ronteltap et al. (2017) was a week. To ensure minimal uptake of heavy metals, source separation with urine diversion (Section X) using a low or no-flush system, which limits the amount of magnesium and calcium in flushing water is advised, because most toxic contaminant risk is posed by faeces (Section X). This slows the struvite precipitation process, which in turn extends storage time and increases the purity of resulting phosphate precipitate with regard to heavy metals.

In another study conducted by Uludag-Demirer et al. (2005) on NH_4^+ removal efficiency in struvite precipitated from anaerobically digested manure addition of Mg^{2+} ions at a concentration of 0.06M in the form of $MgCl_2 \cdot 6H_2O$ resulted in >95% $PO4^{3-}$ removed in precipitate. This was higher than removal rates for effluent for effluent treated with Mg(OH)2 at the same concentration. The study also found that adjustment of pH to 8.5 did not alter removal efficiency in any significant way. As mentioned above, pH is one of the main parameters controlling quality of precipitate. It also affects macronutrient concentrations differently (Section X), so that NH_4^+ -N concentration decreases with alkalinity increase whereas $PO4^{3-}$ -P increases several hundredfold.

While urine contains small amounts of heavy metals, pharmaceuticals may be found in high concentrations. The research by Kemacheevakul et al. (2014) also looked at the removal of broad-spectrum antibiotics (tetracycline, demeclocycline and oxytetracycline) at various retention times and found it to be fastest with 5 days of storage time, achieving 99% removal with additional removal occurring at slower rates. Removal from spontaneous precipitation over time could be a result of degradation or increased alkalinity influencing structure of pharmaceuticals. A study on struvite precipitation from swine manure by Cai et al. (2020), has found that both tetracycline and antibiotics resistant gene (ARGs) transport is likely strengthened by the presence of heavy metals in effluent. Though concentrations are higher in this kind of effluent due to some heavy metal compounds being used for growth promotion, the impact remains the same. Further research is needed to find out whether organic matter, too, plays a role. High concentrations of tetracycline and ARGs could lead to accumulation in food crops.

HIAS WWTP in Hamar, Norway produces struvite approved and certified for use as fertiliser on farmlands, parks, in pots and private gardens based on the international standard for management of environmental systems (EMS) NS - EN ISO 14001. This standard is the most robust and holistic of standards pertaining to environmental management. Table 2 shows the composition of struvite produced at the plant.



Content	Concentration		%TS
Ammonium-N (NH_4):	54000	mg/kg TS	(5,4%)
Nitrogen (N):	54000	mg/kg TS	(5,4%)
Fosfor (P):	116000	mg/kg TS	(11,6%)
Kalium (K):	308	mg/kg TS	(0,03%)
Kalsium (Ca):	1190	mg/kg TS	(0,119%)
Magnesium (Mg):	92400	mg/kg TS	(9,24%)
Natrium (Na):	24,7	mg/kg TS	(0,00247%)
Bor(B):	2	mg/kg TS	(0,0002%)
Kobolt (Co):	0,99	mg/kg TS	(0,000099%)
Kobber (Cu):	2,14	mg/kg TS	(0,000214%)
Jern (Fe):	2430	mg/kg TS	(0,243%)
Mangan (Mn):	211	mg/kg TS	(0,0211%)
Molybden (Mo):	0,144	mg/kg TS	(0,000144%)
Svovel (S)	86,9	mg/kg TS	(0,00869%)
Sink (Zn):	4,99	mg/kg TS	(0,000499)
Kadmium (Cd):	>0,01	mg/kg TS	(>0,00001%)

<0,086 mg Kadmium (Cd) per kg Fosfor (P)

Table 2: *Elemental composition and concentrations of nutrients (macro and micro) and heavy metals in Struvite produced at HIAS (Adapted from HIAS factsheet a).*

HIAS has furthermore tested the efficacy of using biofilm carriers for biological P removal on effluent from three WWTPs in Norway. Effluent flows through a Moving Bed Biofilm Reactor (MBBR) from an anaerobic zone, towards an aerobic zone, before being mechanically returned to an anaerobic phase (Saltnes et al., 2016).

They found that the method succeeded in reducing P concentrations to 0.1mg, particularly in the presence of C sources needed for P accumulation by polyphosphate accumulating organisms (PAO); capable of assimilating P. These microorganisms use their own polyphosphate reserves and release phosphate before being sent into an aerobic zone. Within this zone, OM reserves contained within the cellular constituents of PAOs are used to integrate polyphosphates once again into the microorganisms' cells. Despite phosphate being released in the anaerobic zone, the amount is lower than that taken up again in the aerobic zone.

3.6 Soil amendment and remediation

We have degraded one third of the planet's topsoil and some two thirds of its soil is desertifying. The use of chemical fertiliser has covered up and continues to cover up the symptoms of soil degradation all over the world. Provision of nutrients is not sufficient to address pressing concerns regarding food security in the context of land degradation and loss of arable land under increasingly unpredictable weather and climate conditions.

Soil is made up of an organic component, generally found at the top of the soil profile, and a mineral component, with soil organic matter and degree of bedrock degradation decreasing down the soil column. It has a complex fabric of variable physical and chemical characteristics which are important for healthy plant growth and affect the efficiency of fertiliser application. Both aerobic and anaerobic microorganisms play important roles in nutrient provision, improving soil structure and breaking down organic matter. For agricultural purposes, looser soil in the upper soil layer is preferred as it lets plants' thin and growing roots penetrate deeper into the earth, encouraging aeration in the root zone while allowing rain and meltwater to percolate instead of becoming runoff due to compacted soils.

Humus is a colloid made up of organic matter which has undergone generally complete decomposition and exists in complexes alongside polysaccharides (excreted by microalgae), lignoproteins and polyuronides amongst other bioactives. The presence of microalgae encourages the formation of such humus complexes and improvement in soil quality. Colloidal humus coagulates with soil's other colloid: clay, stabilising structure by encouraging aggregation (Hillel, 2004). Humus is, alongside clay, of high importance to cation exchange capacity (CEC) of soils and proper provision of plant nutrients. Humus has a significantly higher CEC than clay, while they are both negatively charged.

Generally speaking, the darker a soil the higher the rate of decomposition. One therefore finds the highest concentrations of humus in the topsoil of black chernozem, such as that found in the Ukrainian plains; while being nearly non-existent in desert soils. Algae has been used in wastewater bioremediation efforts since the 1960s, pioneered by William Oswald who studied the important interaction between bacteria and algae (Section X). The use of cyanobacteria in bioremediation efforts can improve multiple soil chemical and physical properties. Soil aggregation is encouraged by their presence, thereby leading to reduction in soil erosion during increasingly intense precipitation events (Chatterjee et al., 2017). This is a valuable resource considering the intensification of the hydrological cycle in the global north, as well as the presence of clay-bound P in agricultural lands and catchments. In clay-rich Norway, for example, this is of great concern and has led to eutrophication of water bodies, to the detriment of flora and fauna, while complicating water management. Additionally, using cyanobacteria improves physical properties such as soil temperature and aeration.

While urine is the most nutrient dense component of excreta, making it a valuable source of biofertilizer, composted faeces has benefits for soil amendment by improving the physical qualities of soil such as soil water holding capacity and aggregation, while contributing OC and counteracting the loss of organic topsoil. Degraded soils include degraded agricultural areas, contaminated soils and ecosystems following desiccation by fire (Gonzalez-Gonzalez and de-Bashan, 2023).

With changing climate and increasingly unpredictable weather, an intensified hydrological cycle may lead to significant changes in salinity and sodicity in the global north and global south. When rainfall happens suddenly and intensely, areas with more sand and gravelly soil, and less organic topsoil, may experience a greater recharge of groundwater than if rain falls slowly and warmer weather evaporates large portions of it before it percolates into groundwater. Conversely, where there is more clayey and compact soil with smaller particles and pore sizes, there may be more surface runoff and less groundwater recharge. As salinity patterns change quickly in response to changes in precipitation (Gonzalez-Gonzalez and de-Bashan, 2023).

Improving soil structure in order to increase water holding capacity may help counteract negative impacts on salinity and the loss of arable land. Desert encroachment in North Africa.

Desertification of agricultural areas resulting from climate change has been and continues to pose great risks to food security. The stage preceding desertification of soils is their salinisation or sodification, with subsequent alkalisation. Increased soil salinity, despite being of greater concern in arid and dry areas of the African continent, is a challenge both in the global north and south. Some salts contributing to salinisation and sodification are Cl-, CO3 2-, SO4 2-, NO3-, BO3 3- and HCO3-, of Na, Ca, Mg, K and Fe (Bui, 2017). Such soil degradation has led to decreased food security through reduction in agricultural productivity and soil quality, while causing damage to roads, buildings and important heritage sites, and reducing wildlife diversity and water quality (Amezketa, 2006). Saline soils are defined as those containing >15% exchangeable N and an electrical conductivity >4dSm-1 (Bui, 2017), while sodic soils contain high levels of N carbonates, causing increased alkalinity (rise in pH). Alkali soils are sodic, and vise versa, as they contain NAHCO3 and Na2CO3. Algae can reduce concentrations of exchangeable Na in soils, thereby regulating pH and providing routes for soil reclamation and remediation (Chatterjee et al., 2017). In arid areas where evapotranspiration tends to be higher than precipitation, salts can precipitate out of soil due to little downward leaching (Bui, 2017). In areas that shift between drought and waterlogging, only organisms adapted to such extreme conditions may be able to survive.

There is great value in preserving wild crops more adapted to drought and soil salinity, increasing resilience by diversifying crops and allowing adaptability in the face of unpredictable and changing climates. In certain cases where regulating salinity is especially difficult, the integration of genetic material from wild varieties and landraces through plant breeding is necessary to improve food security and amend soils. This can be in conjunction with application of biofertiliser and biostimulants recovered from organic household waste. Agricultural extension offices and farmers' field schools may be set up in affected areas to increase and exchange knowledge on crop breeding, soil remediation, production of biofertiliser and biostimulants, as well as sustainable intensification methods.

One severe example of soil salinisation and sodification comes from the Egyptian Nile Delta, one of the world's most vulnerable regions to the impact of climate change, where the governorates of Alexandria and Beheria have particularly been affected (Abu-Kota et al., 2024). Due to geographic location (bordering the Mediterranean Sea) and the area's geological makeup, saltwater intrusion into groundwater is difficult to prevent. Rising sea levels caused by climate change also threaten to submerge large areas along the Nile Delta, subsequently increasing soil salinity. Land degradation and poverty are inextricably linked in the region due to high reliance on agriculture as a source of income and subsistence, with population growth encroaching on agricultural lands. These externalities must be considered, as desperate people cannot always afford to think long-term and will understandably opt for available options; often high N conventional fertilisers. Examples would be effectivising biofertiliser production to reduce financial burden on farmers, and improving access of marginalised communities to education and family planning, which plays an important role in reducing and delaying natality. A combination of short- and long-term solutions is necessary.

Microalgae can also assist in reclamation of contaminated soils as microalgae-bacteria consortiums can break down contaminants into less harmful substances and may reduce our dependency on chemical-based treatments (Gonzalez-Gonzalez and de-Bashan, 2023).

It is worth mentioning that it is counterproductive to work on restoring soil health and limiting human and animal consumption when we continue applying POPs in the form of pesticides to crops. There must be a holistic approach where such is possible. Shifting to the use of more readily biodegradable and less persistent organic insecticides such as pyrithrins instead of persistent and toxic organochlorines and organophosphates. As pyrithrins are non-specific insecticides their natural and synthetic, somewhat more persistent, forms should be applied in liquid form to avoid volatilisation and migration away from the application point. Carbimids, which also have short residual toxicity may also be used. To avoid toxic consequences to non-target insects such as bees, application should be precise and ideally occur at night. It is also possible to practice push-pull pest management, where valued crops are intercropped with repellent plants which “push” pests away and surrounded with sacrificial “pull” plants that attract them.

4 Legal frameworks

Currently, the main obstacles to the ability to market fertiliser produced from parent substrates of human origin are absence of legal frameworks and possible social obstacles in the public willingness to shift conventional “flush and forget” sanitation -the public does not necessarily have to contemplate the fate of its waste, into sustainable and recovery-focused sanitation.

In 2019, the European Commission (EC) expanded upon the 2003 regulations ((EC) 2003/2003) pertaining to fertilisers, as proposed by the EU “Circular Economy Action Plan” of 2015 (COM/2015/0614) by including “secondary-raw-material-based fertilising products” (p.2). These consisted initially of struvite, biochar and incineration ashes, abbreviated STRUBIAS; but the definition was broadened to include all phosphate salts, as well as all products of thermochemical transformation processes. STRUBIAS therefore grew to include precipitated phosphate salts and derivatives; thermal oxidation materials and derivatives; and pyrolysis and gasification materials. Requirements in the revised regulation pertained to “Intended function” -e.g. liming, fertilisation, soil amendment etc.; and “Component materials” which were to be divided due to varying safety requirements for ensuring pollutant removal and degradation. In the case of expanded biochar and incineration ash definitions, component materials are distinguished by oxygen supply during thermochemical processes; distinguishing it from pyrolysis and gasification.

The primary risks identified in the updated regulation were the recycling of contaminants via insufficient treatment and the production of transformation products or de novo contaminants. Noteworthy is the fact that in the case of contaminants of emerging concern, guidelines were difficult to establish due to little knowledge about interactions between various contaminants and impact on human health. In the case of certain contaminants such as pathogens, metals and POPs guidelines and quality requirements were proposed.

As mentioned earlier on, phosphate salts occur in other forms than high-purity struvite. The revised regulations mention that focus needn't be on such high-purity precipitated phosphate forms that are not superior to less pure forms and still valued in the industry, nor having superior horticultural applications due to technical and monetary challenges/cost in production processes. Furthermore, the low occurrence of OC in such precipitates tends to reduce levels of contamination in the end product (p.37) -OC may be used as an estimate of product purity. The proposed OC limit in the revised regulation was 3%, due to the inclusion of phosphate salts containing impurities, known to encourage contaminant adsorption to its reactive surface and therefore be detrimental to human and environmental health (p. 55). No such limit is set in the DIN spec (91421:2020-12), which does not necessarily constitute a shortcoming as other contaminant parameters and limits are specified. It may, however, be of value to measure OC content regardless, to further our understanding of the role OC plays as an impurity vector and further improve upon treatment methods, particularly with regard to antibiotics, ARGs, biological pathogens and volatile and persistent organic pollutants. Intermediate forms of P may also be recovered from sources with low plant availability (e.g. hydroxyapatite (HA)) followed by mobilisation of precipitate into more available forms of P.

In 2018 the first fertiliser produced from human urine (Aurin) was approved in Switzerland (DIN spec, 2020). Switzerland is also the first country to require P recycling from wastewater and sewage sludge beginning in 2026, while the same regulation comes into effect in Germany in 2029 for waste containing 20g P/kg (Sichler et al., 2022).

The DIN spec, presented in 2020, provides much-needed guidelines for enabling quality assurance on safety, marketability and nutrient recovery potential of various alternative fertilisers. The existence of concrete requirements allowing for marketability would also enable easier dialogue with and provision of assurances to policymakers and the public, alike. These specific guidelines, based on present regulation on fertiliser in the EU on both recycled and synthetic mineral fertiliser, is based on preventing harm to the environment and humans.

5 Transformation and resilience

"the only way to make a forest fireproof is to burn it"

Transformation is *"the altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems)"* (IPCC, 2012, p.564).

Resilience is *"the ability of people, households, communities, countries, and systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth."* (USAID, 2023, p.5) while ensuring the *"preservation, restoration, or improvement of"* a system's essential basic structures and functions (IPCC, 2012, p.563).

Holling (1973) was the first to define resilience as the ability of a system to tolerate stressors or perturbation without shifting into a different system. These changes are described within the literature as regime shifts, tipping points or catastrophic events/shifts; they all mean the same thing (Dakos and Kéfi, 2022).

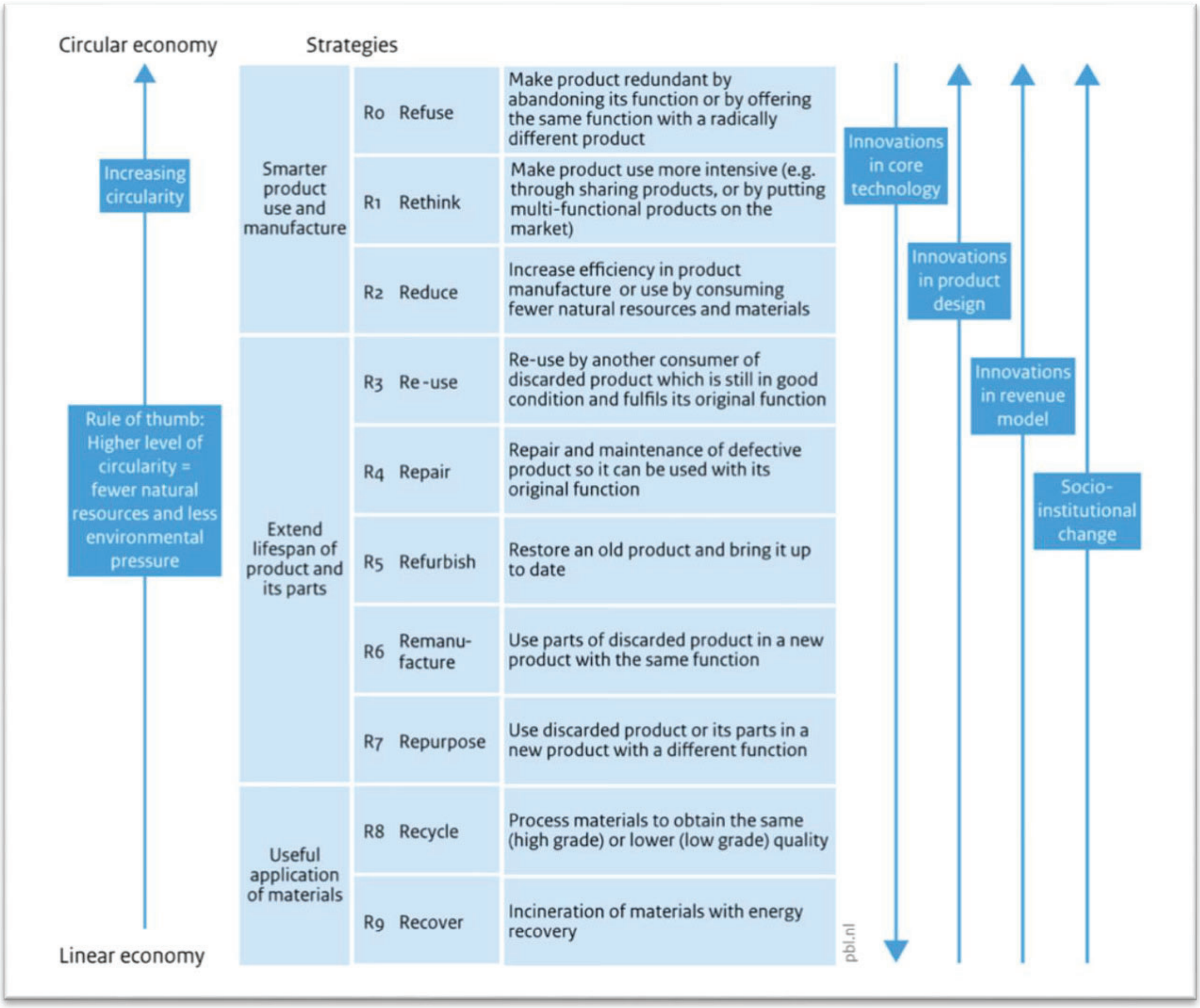
Within much of "development" discourse focusing on climate change, adaptation is treated as an apolitical, tech-positivist approach aiming at its core to save the economy –whatever that vague promise means. According to Pelling (2011) *"Adaptation has been framed in terms of what is to be preserved and what is expendable, rather than what can be reformed or gained"*. Furthermore, they argue that adaptation is rather a social and political act, providing opportunities for reform within socio-ecological and socio-institutional systems. In a sense, resilience is the buffering capacity of systems, and can be applied to a multitude of fields. Resilience may be related to engineering, psychology, "development", socio-ecology or ecology.

A resilient system is allowed to probe its boundaries, increasing its resilience slowly but surely over time in the face of stressors. A simplified, controlled system is not able to do this, as veering outside the artificial limits is essentially neither possible nor permitted; deviations do not function in a constructed, rigidly and narrowly defined system. Furthermore, the loss of deviant crops, reliance on single sources of fertiliser or the loss of biodiversity which may contribute to said resilience, mean that stressor events –e.g., speeding up the hydrological cycle or flash flood events, drought, increased salinity of soils, rises in temperature and atmospheric carbon loading etc.., bring systemic failure to light, whereby the simplified system itself *is* the failure, and boundaries are reshaped and narrowed, with the burden of adjusting them being relegated to technoscience, forcefully and defensively -as opposed to organically. If biodiversity is reduced, and drought or salinity resistant wild crops or deviant landraces are lost, the artificial basin only gets smaller and smaller.

6 The circular economy

Alongside the green economy and green growth concepts, the circular economy (CE) has gained traction as an operationalization blueprint for businesses to achieve sustainable development (Kirchherr et al., 2017). A common understanding of what the concept entails should be reached. Our ability to intuit key elements of non-linear system does not necessarily consider the actual complexity involved and there is risk of becoming trapped in a state of '*conceptual contention*'(p.) if a collective understanding is not arrived at. It makes collecting data and sharing knowledge harder if terms are not clearly defined and the scope of CE established. It makes it hard to build on previous knowledge or even create it. Reuse, reduce and recycle, or the 3Rs, are most commonly included in the definition of CE with reuse and recycle

Kircherr et al. (2017), after examining 114 definitions of CE, found that the 3Rs: "Reduce, reuse and recycle", were most commonly used. The EU Policy Framework on CE also includes "recover", to make the 4R framework, but this combination was rarely used. One expansive definition of CE is the Potting et al. (2017) 9R Framework (Figure 7) written on behalf of the Netherlands Environmental Assessment Agency (PBL), focusing on product chain development. It is an expansion on the traditional "waste hierarchy". The recovery of resources from organic household waste is a preventative measure on a centralised and decentralised level.



Figure

Figure 7: Degrees of circularity within the product chain. Adapted from The Council for the Environment and Infrastructure (RLI, 2015) and edited by Potting et al. (PBL, 2017).

Here degrees of circularity are ranked hierarchically, with peak circularity being *Refusal*. An interesting aspect to this is that increasing circularity entails increased requirement for socio-institutional change. This can be linked to the previously discussed need for transformative, versus merely adaptive or mitigative climate change action (Section X). Potting et al. (2017) describe this as a shift in our collective normative thinking, a triggering of *"profound changes to our cognitive structures"* (p.6). Instead of functioning as miners in an exploitative linear relationship, or as described by Gregson et al. (2015) a *'take-make-dispose'* mindset *'with raw materials in at one end and externalized wastes at the other' (p.3),* our waste becomes a resource and in doing so allows humanity to insert itself (back) into circular systems.

Legal frameworks on *recycled products from parent substrates of human origin* (DIN SPEC 91421:2020-12, p.5), or rather the lack thereof, are an obstacle to marketability and normalisation of fertiliser and soil amendments made from human waste. Again, this increases the degree of circularity due to the need for socio-institutional change in legal standards -in this case creating them.

Salmenperä et al. (2021) observed a distinction when dividing practitioners into developers and intermediaries, working on pilots relating to waste management. Developers were found to lack systemic thinking, focusing on barriers directly pertaining to their objects of development; the things right in front of their noses. Intermediaries, on the other hand, were more able to identify barriers across different stages of the supply chain. But perhaps there is something to be said about navel gazing within disciplines and between silos as a barrier in and of itself. This also entails space being held for anecdotal and traditional knowledge, an opportunity to treat peoples with an enormous amount of insight as valued contributors and partners, not just sinks of knowledge to be plotted into confined datasets. The qualitative statistics adage goes *not everything that can be counted counts, and not everything that counts can be counted*.

7 Conclusion

What is required in order to achieve a linking of externalities across discipline is instilling *"..an ability to move lovingly at landscape speed through fields and communities, sampling, measuring, analyzing, and pondering; an ability to listen closely to people engaged with the land and indeed everyone with something interesting to say; and an ability to elaborate and illuminate general theory from an extraordinary grasp of the telling detail*"(Nabhan, 2008) in students and scientists, encouraging cooperation. We must remember that disciplines should reject ridicule; which, to paraphrase astronomer J. Allen Hynek, is not part of the scientific method and neither academics nor the public should be taught that it is while breaking down the false dichotomy of the sciences. As Lao Tzu says in the Tao te-Ching *"...enumerate the carriage parts -still not a carriage",* we cannot see the forest firmly pressed a single tree.

An expert's role when encountering traditional or anecdotal knowledge may be to establish the difference between correlation and causality. For refusal to achieve its intended goals, the third-party effects, forcings or externalities must be clear, so sustainability does not become performative. Achieving such an understanding requires communication and collaboration between expert/expert and expert/non-expert across fields. We move closer to CE by understanding and linking forcings both biotic and abiotic.

The standardisation of crops has also created an expectation amongst consumers regarding the acceptable appearance of produce. To put it simply, there is an image of what an ideal potato *should* look like, and if a potato does not live up to that expectation it is discarded as subpar –by both producers and consumers. The case of supermarket tomatoes developed in the US during and in the aftermath of the second world war in response to manual labour deficits is an interesting one. Tomatoes were bred purely with uniformity and machine compatibility in mind and ripened artificially to arrive on shelves in pristine -caricature of a tomato- condition. Flavour left, and still leaves much to be desired. The nutritional value and taste of crops are externalities when foods are produced much as one might produce car jacks or buttons or sweaters. And it is not only the crop that is adapted to suit the machine. Fields are levelled flat for ease of sowing and harvest, while watercourses are shifted and piped. These are all linked to resource recovery, as non-linear thinking requires.

Though it may seem like an overreach, the acceptance due to ease of access to such vegetable ideals and fast food (be it ultra-processed or not) can be linked to a deeper devaluing of the rituals of consumption. Taking more of a bird's eye view, the devaluing of sustenance to simple *sustenance* has been driven by the productivity requirements associated with increased consumerism. People are pulled away by the need to obtain moneys to sustain themselves by producing supermarket tomatoes so they may purchase supermarket tomatoes consumed at separate tables –or on the go- because they do not have time –because they must obtain moneys to...and so on and so forth and so it goes. It would still be arrogant to place the entirety of transformation burden on consumers. The socio-institutional and socio-economic externalities, third-party effects or forcings (whatever we call them) must be taken into account; otherwise, systemic failures are bound to occur.

There is a difficulty in assigning blame, and thereby assigning the burden of both restitution and rehabilitation. The guilty party is obvious when there is an oil spill, insofar as those responsible are known, but they remain a multinational company as opposed to individuals and are in a sense mere purveyor of a good there is an enormous market for -a large number of individual consumers. Rainforests would not be cleared to make space for soy farms had no one wanted to consume beef -granted alternative sources of protein are available, of course. *No* is more powerful than technology. On the other hand, this cynical view ignores the fact that such corporations are exploiting an immediate need, a need created due to the structuring of societies around production and productivity. Achieving normalisation of such products requires working from the top-down and bottom-up at the same time, at the grassroots and policy levels. Shifts towards recovery-focused solutions within sanitation operate at a high level of circularity, due to the requirement for transformation within the legal framework, as well as shifts in social perception and acceptability.

There exists a great deal of research and knowledge, both expert and non-expert, on non-linear sanitation systems. Likewise, we know precisely how to make gold out of our waste. The question is not: can we? The question is: how do we make this the norm? I believe the answer is through continued research on links between various biotic and abiotic factors, expansion of technical knowledge to ensure safe and effective treatment and production, the inclusion of traditional and anecdotal knowledge, stakeholder inclusion and working at both top-down and bottom-up levels. Resource recovery from organic household waste provides a promising and safe avenue towards achieving food and water security, while counteracting the detrimental impacts of climate change on the environment and society.

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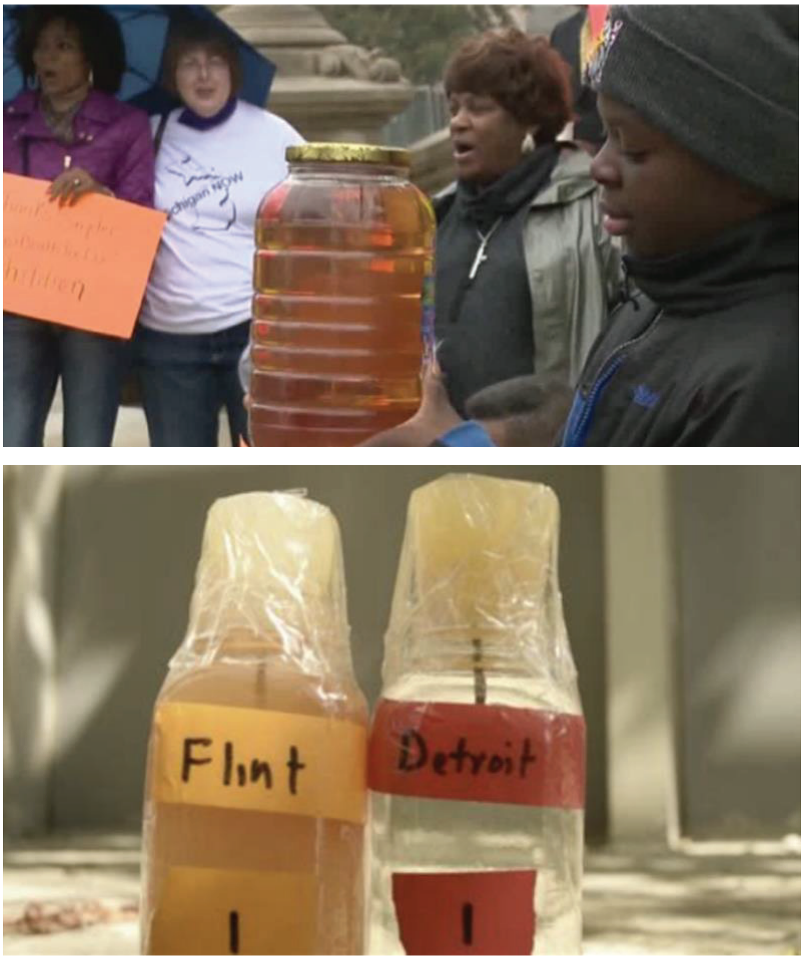
Appendix

The Flint water crisis (2014-2015)

In a cost saving initiative, beginning in 2014, the population of Flint, Michigan had their water supply shifted from Detroit's water system (Lake Huron) to the Flint River system, without assessing the safety of this new water source. The state of Michigan, having saved approximately $7 million on the scheme, chose to ignore the deluge of complaints and reports from residents concerning the, at first, aesthetic quality of their potable water. It smelled of rotten eggs, tasted awful and was a muddy brown colour. This potable and agricultural water was in fact contaminated with lead, due to old leaded pipes being used in conjunction with the high corrosive nature of the Flint River system, as well as lack of anti-corrosives in said pipes. It was not until children began showing signs of lead's neurotoxic effects, contracting Legionnaire's disease; a severe form of pneumonia, that stakeholders were taken seriously – or rather more myopically, people in charge realised this would cost them far more than they had saved. 100,000 residents were then left without access to potable water, and 12 people or more died from the pollution. It has been argued that this is not only an example of irresponsible governance and planning but an outcome of deeper systemic racism and classism–due to the racial and economic makeup of the Flint community; >60% of Flint's population is comprised of persons of colour (POCs), and about 40% lived below the poverty line. Lead concentration upwards of 397 parts per billion (ppb) were measured, with the US EPA listing a maximum safe level of 15 ppb. The $7 million the state saved on the scheme turned into a $626 million settlement paid out to the affected children, families and businesses of Flint who had paid for a service they did not receive (BBC, 2021).



Top: A local child holding up a jar of lead tainted water at one of many protests which took place between 2014-2016. Bottom: A comparison between water from the Flint system and the Detroit system -which was used prior to 2014.

Arsenic pollution in Bangladesh and east India

A well-known case of As toxicity arising from non-anthropogenic sources but due to anthropogenic activity comes from Bangladesh and eastern India. In the 1970s, residents of these areas were encouraged to pump groundwater from the Ganges-Brahmaputra-Meghna Delta due to bacterial contamination of surface waters and the, often true, assumption that groundwater would be safer as it is more protected from surface pollution. This was a project by UNICEF and the World Bank, with the intention of meeting safe water drinking goals. Groundwater had already been used as a source for irrigation. Tens of thousands new wells, assumed and intended to be safer than the polluted surface waters, led to grave ecotoxicological consequences in the 20-30 million residents, currently at 50 million, who began using groundwater for domestic purposes (vanLoon and Duffy, 2011); slowly but surely poisoning an entire nation. Already in the 1980s, patients began presenting with skin legions which, in the worst of cases, devolve to cancer, cardiovascular disease, and other illnesses. An estimated 40,000 people die of arsenic poisoning each year in Bangladesh. Arsenic is highly insoluble and found in trace amounts within the Delta in the form of arsenides associated with sulphide minerals. The actual source is not yet understood but hypotheses exist. These include: the oxidation of minerals leading to release of arsenate and arsenite into water due to reduction in groundwater levels, the reduction of Fe_2O_3 minerals sorbed to arsenic which undergo reduction in anoxic organic-matter rich sediments, and fertiliser derived phosphates dislocating arsenite and arsenate from sorped sites (vanLoon and Duffy, 2011). As the true cause of As pollution is not yet known, preventative efforts have been difficult to establish. Presentative efforts have therefore been focused on establishing the safety of individual wells, as wells vary greatly in arsenic concentrations, by distinguishing them via markings (Photograph X).

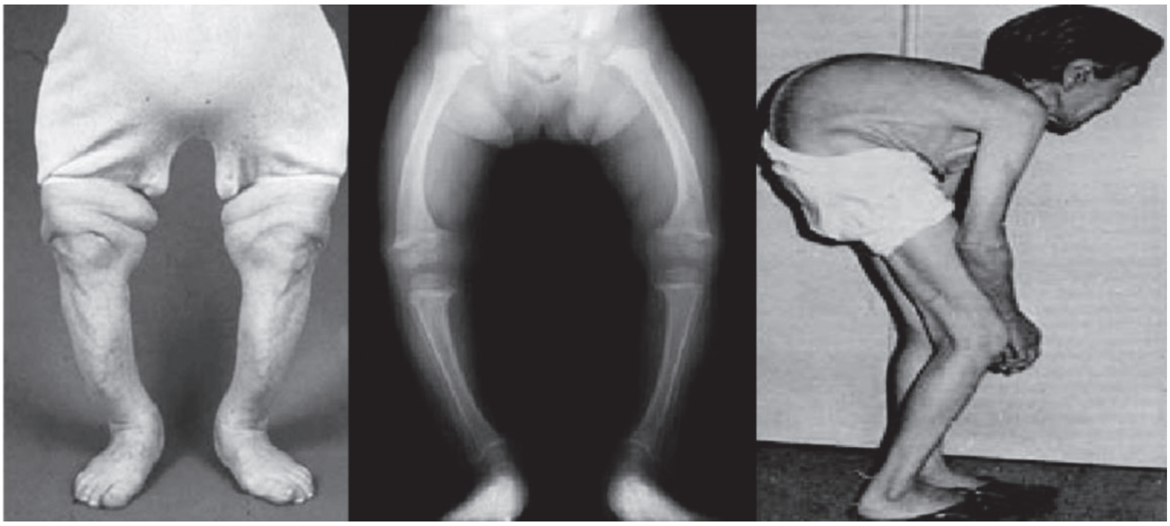
A survey conducted in ?? measured As in groundwater from "64 districts in the country and found that 59 had concentrations >10µg L−1 and 43 had concentrations >50 µg L−1" (Hossein, 2006, p.1). The safe concentration of As in drinking water according to the WHO is 10 µg L−1. Some 97% of the population in Bangladesh rely on groundwater as a potable water source.

A Bangladeshi person with hyperpigmentation on their left hand, and the loss of two fingers on the right due *to arsenic damage (Rafiquar Rahman for Reuters, 2015)*

Top Left: A well designated as safe by the colour green. Top Right: A Bangladeshi person carrying a marking designating a well as unsafe using the colour red. Bottom: An overview map of safe and unsafe wells.

itai-itai disease, Japan

The name of this disease translates from Japanese to “it hurts-it hurts”; the words spoken by patients arriving at hospitals in agony. It resulted from pollution of the Jinzu River Basin in Toyama prefecture, Japan. The source was an upstream zinc mine named Kamioka mine, operated by the Mitsuni mining and smelting company (Kaji, 2012). The first cases, not yet understood, appeared in the early 1900s and it was not until the 1960s that Cd pollution of rice paddies was identified as the source. Cd often appears in minor quantities in Zn deposits and as such is a byproduct of Zn mining. Between 1910-2007 ca.400 people, have been affected. The disease causes severe bone pain, fractures, pseudo fractures (Looser's zone) and renal tubular dysfunction. The bulk of those affected were women, likely due to their lower bone mass density and weight.

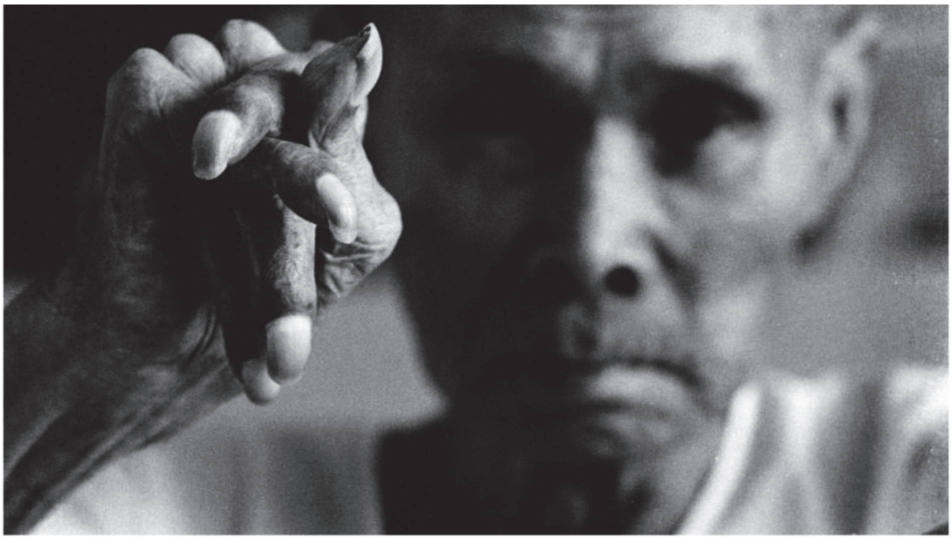


Photograph X. Child suffering from itai-itai disease, presenting with change in bone structure. Original source unknown. Adapted from Dökmeci and Ongen (2009).

Minamata Bay disease, Kumamoto and Niigata prefectures, Japan

In the city of Minamata within the Kumamoto prefecture in Japan, locals began showing symptoms of a central nervous system disease in 1956 (Ishikawa and Ikegaki, 1980). A second disaster occured in 1965, dubbed the second Minamata Bay disease, or Niigata Minamata disease where locals surrounding the Agano river in the Niigata prefecture were subjected to the consequences of mercury-containing industrial wastewater being dumped into the river (Ishikawa and Ikegaki, 1980). The company responsible was in 1968 found to be the Chisso Company; renamed Japan New Chisso (JNC) in 2012. The source was the release of organic methylmercury due to inorganic mercury's use as a catalyst in the production of acetaldehyde at the plant. The dumped industrial waste containing bioavailable and neurotoxic organic mercury accumulated first in shellfish and fish through absorption by skin or gills and up the trophic scale until it reached the human population, which was heavily reliant on fish protein. Some 100 people lost their lives as a result, with many becoming disabled (Walker et al., 2012). The impact of both these disasters was exacerbated by the affected population's dependence on fish as their primary source of protein. Populations with a low diversity in diet are less resilient and more at risk from such catastrophic events (Walker et al., 2012). Today there are approximately 3000 humans recognised as victims of Minamata disease. A depressing fact is that governmental acknowledgment of the disease's source came in 1968, the year an economically viable alternative to mercury in acetaldehyde production became available.

According to the Minamata disease museum's website the symptoms include *"numbness and unsteadiness in the legs and hands, tiredness, ringing in the ears, narrowing of the field of vision, loss of hearing, slurred speech, and awkward movements. Some early severe victims of Minamata disease went insane, became unconscious, and died within a month of the onset of the disease.*
There are also victims with chronic Minamata disease symptoms, such as headaches, frequent tiredness, loss of the senses of smell and taste, and forgetfulness, which are not easily visible but make daily life difficult. Moreover, there are congenital Minamata disease patients, who were born with handicaps after being attacked by methyl mercury while in the wombs of their mothers who consumed polluted fish. No cure for Minamata disease has yet been discovered, so treatment consists of attempts to lessen the symptoms and physical rehabilitation therapy. In addition to the physical damage, there is also social harm, such as discrimination in relation to Minamata disease."



Photograph X. Iwazo Funaba, a person with Minamata Disease, taken 10 years after its onset. Photograph by Shisei Kuwabara, 1970.

Photograph X. Tomoko, a victim of Minamata disease, celebrating her "Coming of Age Day" with her father. Photograph by Shisei Kuwabara, 1977.

Thallium

Photographs X. Left: 42-year-old patient presenting with infected acneform lesions, lip oedema, and angular stomatitis on day 13 of illness. Right: Alopecia on day 45 of illness. While many signs and symptoms of thallium poisoning may be conflated with those of arsenic poisoning, alopecia is highly indicative of the former (Misra et al., 2003) Thallium poisoning should also be considered in patients presenting with rapidly progressing peripheral neuropathy (nerve damage), regardless of whether alopecia is present (Rusyniak et al., 2002) .

Photograph X. Patient presenting with erosion of proximal parts of nails following thallium poisonin (Saha and Sadhu, 2004).

Testing of physical and chemical parameters

Testing methods for some physical and chemical parameters are provided below, as well as brief discussion of these parameters. These are sourced from the DIN spec, as well as Krogstad and Børresen's Field and Laboratory Methods (2015) and a write-up to videos handed in for fulfilment of GEO220.

Dry matter (DM)

Method : drying

Dry amples are first sieved, spread out onto a tray and placed in a drying cabinet overnight at 35-40°C to hinder microbial activity tampering with the sample before dry matter content determination. Next, 5g samples are weighed into porcelain crucibles –which must also be weighed but tend to be ca. 20g is heated at 105°C for 24 hours. Samples are then cooled and weighed. %DM is found by dividing sample weight before drying by sample weight after drying.

Organic Dry Matter (ODM)

Method: loss on ignition (incineration/calcination)

5%DM

Loss on ignition is a method for estimating organic matter content in samples. It is obtained by first straining samples through a 2mm sieve. Special ceramic bowls are then weighed both with and without a sample (often 5g) to obtain the weight of the sample before drying. Samples are then heated at 105°C for a minimum of 6 hours, after which they are weighed once more. The loss here is water-weight. This needs to be corrected based on clay content, as it is assumed that in clayey samples water is bound more strongly and may not be lost entirely upon heating. Next, samples are heated at 550° C for a minimum of 10 hours - keeping in mind that it takes about an hour to heat up the oven, and weighed again. Loss on ignition in then obtained as a percentage of loss on ignition.

Loss on ignition ensures that samples are rid of organic matter, as well as chemically bound water. It is found by weighing out 5g samples of fertiliser into porcelain crucibles (20mg?) and placing them into a calcination oven. Samples are heated at 550°C for 3 hours, allowed to cool and weighed once more. Loss on ignition is then calculated in % by dividing the decrease in weight of dried sample after calcination by the weight of dry sample before calcination. To comply with requirements presented in the spec, ODM must make up no more than 5% of DM.

Salt content/ Conductivity (in KCl/g):

Method: Conductivity meter in H2O eluate

Threshold 0,5g/l

Conductivity is a measure of the ability to transmit an electrical current. Truly pure water is an insulator. The more ions we measure, the higher its conductivity. This will depend on the concentration of ions, their valence and mobility. Conductivity is an indicator of water's source. While rainwater has a conductivity of about 10µSiemens, groundwater -with its high content of dissolved minerals- tends to be much higher. Conductivity is affected by temperature and is ideally measured at 25C. A conductimeter -the instrument we use to measure conductivity- can correct for temperature variations.

pH

pH, from the latin for power and quantity of hydrogen, is operationally defined as the negative logarithm of the hydrogen ion concentration -log(H+). It ranges from 0 to 14, where 7 is neutral. The more H+ ions we measure, the lower the pH of (or the more acidic) a solution is. The more hydroxide ions OH- we have, and thereby the less H+ ions, the higher the pH and more basic/alkaline it is. There is an inverse relationship between these two. At the neutral pH of 7, their concentrations are equal. It is worth noting, however, that their values are higher than zero, as deprotonation of water molecules will still naturally occur.

A logarithmic scale is used due to the wide range of concentrations we may measure. This tells us that if we have a sample with a pH of 5, for example, and another with a pH of 6 there is a difference of one order of magnitude between the two (by a factor of 10). The sample with a pH of 5 has 10 times more H+ in it than the one with a pH of 6; and consequently 10 times less OH- ions. A sample with a pH of 5 would then have a 1000x higher H+ concentration compared with one with a pH of 8.

PH is technically based on H+ and hydroxide ion *activities*, as opposed to concentrations. This is because ions in a solution interact, which can affect measurements giving false concentration values. While the definition of pH we are familiar with may be true for highly diluted solutions, it is incorrect for samples with a high ionic content. Calibrating the pH scale against concentration is difficult, and results in an approximation. It is therefore, operationally, the effective activity of ions we measure when we measure pH. To make things easier, and obtain comparable results, the pH of samples is conventionally measured by calibrating instruments against buffer solutions with known pH values. Calibration is a vital step prior to measurement.

pH affects the solubility of pollutants and metals, thereby affecting their toxicity, and whether or not they will be transported long distances or become bioavailable, eventually accumulating in organisms and up the trophic scale. It also affects the availability of macro and micro plant-nutrients, which have varying ideal pH ranges depending on their charge, size and other properties. There are varying availabilities of plant nutrients at different pH. Soil with a pH of 7.5 is considered alkaline, and 8 very alkaline; while that with a pH of 5 is acidic, and pH of 4 is very acidic.

In order to measure pH,10ml samples are placed in a graduated beaker with 25ml deionized water and sealed with a lid, after which they are thoroughly shaken and left to sediment. They are mixed once more and left to settle for 15 minutes. A pH meter is calibrated against two buffers at pH 4 and 7 and a standard buffer with a known pH (e.g., 6.87). The meter is made up of a calomel electrode and a glass electrode leaking potassium chloride (KCl) covered in a permeable H+ sensitive glass membrane. These are placed within samples and pH values are noted once they stabilise.

Even though the spec does not specify this, CaCl2 is more reflective of plant experience when fertilised, as introducing some salts increases H+ in the solution (McCauley et al., ??). The author recommends testing in CaCl2 as well as deionised water. This leads to a pH value which is lower by 0.5-0.9 pH units. On the other hand, the electrode itself leaks KCl, a salt, and may compensate somewhat for the naturally occurring salt content in soils (Prasad and Power, 1997). According to the spec, all pH values are to be labelled.

Alkaline active ingredients /alkalinity (CaO)

Alkalinity is a measure of ability to neutralise acids, it gives an idea of a media’s resistance to changes in pH -it is its buffering capacity; its resilience. The higher the mineral content, the more alkalinity is a measure of carbonate and bicarbonate content. In waters with low mineral contents, for example, alkalinity is mostly provided by other basic materials such as humus.

To measure alkalinity we need to titrate. Titration is a process whereby an acid with a known concentration is added to the sample until a particular pH is reached. This means we need to measure pH (Section X) while we titrate. Samples are titrated down to a pH of 4.5. At this pH it is assumed that all bicarbonates (HCO_3^-) have been converted to carbonic acid ($H2CO3$), or to put it in other words -that the buffering capacity has been “used up” in samples with pH lower than 8.3. In samples with a pH greater than 8.3 , where hydroxides also contribute to the buffering capacity, carbonates ($CO2{-}3$) are titrated to bicarbonates at pH 8.3 and to carbonic acid at pH 4.5.

Method

Dissolved samples with measured volumes are titrated against HCl down to pH 4.5. The volume of titrant is noted, alongside the HCl concentration and used to calculate alkalinity using the following formula, where C is concentration and V is volume:

Total alkalinity (mmol/l) = $(C\mathrm{HCl} * V\mathrm{HCl} * 100) / V\mathrm{sample}$

According to the spec, the threshold for alkaline active ingredients is 5% of dry matter content.

Phosphate (P2O5)

Extraction in aqua regia (a mixture of nitric and hydrochloric acid in a molar ratio of 1: 3) and atomic emission spectrometry (ICP-OES) There are two acknowledged methods for determination of phosphate content, these are digestion in aqua regia (a mixture of nitric and hydrochloric acid in a molar ratio of 1: 3) under reflux conditions or using a microwave, or followed by ICP-MS or ICP-OES; or via addition of molybdate and determination using spectrophotometry at 880nm. The former is recommended for measurement in the DIN spec, while the latter follows the recommended standard NS-EN-ISO-6878 in the norwegian "forurensningsforskriften” (ref).

Heavy metals (As, Pb, Cd, Cr, Cr(VI), Cu, Ni, Hg, Tl, Zn);

Heavy metals have been discussed in (Sections X). When ionised they are cations; positively charged ions and can therefore be measured using Inductively coupled plasma optical emission spectrometry (ICP-OES) per the spec requirements. The noble gas argon (Ar) is introduced into a chamber and ionised to plasma by heating to 1000K (726,85 °C; 1340,33 °F). Samples are sequentially introduced into the chamber as a fine aerosol mist and the influx of energy causes electrons in their outer orbital to "jump" up an energy level/orbital. This is a cascade effect, whereby atoms “crash” into one-another leading to a chain reaction of ionisation. Upon reaching cooler areas of the chamber these electrons jump down an energy level and that additional energy is emitted in the form of light (photons) at specific wavelengths. Various measured wavelengths are then compared against standards to determine both concentration and species of cations. An issue which might arise here is that some metals may have very similar wavelengths. In the spec, all heavy metals are measured in this way; the exception being chromium (VI). Cr (VI) is measured through extraction in demineralised water and photometric determination of Cr (VI) 1,5 diphenyl carbazide.