DECEMBER 2022

710078542

C40 CITIES

P-CYCLING

URBAN NUTRIENT RECOVERY FROM URINE TOWARDS RESOURCE CIRCULARITY

SUMMARY

To respect planetary boundaries and ensure global food security, society must become more circular and recycle all waste. Biogeochemical flows of nitrogen and phosphorus are among the most transgressed planetary boundaries. Fertilizer runoff and sewage containing nitrogen and phosphorus are dumped into rivers and coastal waters, killing aquatic life through eutrophication. To combat this, human urine, which is rich in the fertilizing nutrients nitrogen and phosphorus, should be diverted and recovered from wastewater and used as fertilizer. This could replace 19% of nitrogen and 22% of phosphorus demand at maximum estimates.

Urine diversion is safe and there are many techniques to accomplish recovery. It reduces energy use, water, and greenhouse gas emissions compared to traditional wastewater treatment plants and extends the life of plants by reducing load. Though urine is subject to cultural taboos, people are accepting of the idea globally. It is as or more effective than synthetic fertilizers.

To accomplish this, C40 Zero-Waste signatory cities must adopt a circularity mindset for wastewater and build the infrastructure to transport and process urine. Then, cities must use the proven tools of efficiency standards, building codes, and tax incentives to drive widespread adoption of urine diverting toilets and collection infrastructure. These policies will help cities become more self-sufficient and work towards global food security.

C40 CITIES

Policy Recommendation Highlights

- C40 Zero Waste signatory cities should **adopt a circularity mindset** on wastewater
- **Urine should be utilized as fertilizer** to address food security and planetary boundaries
- **Cities should invest in infrastructure** to transport and process the urine and add collection infrastructure to municipal buildings
- Cities should use building codes, efficiency standards, and tax incentives to **increase adoption** in privately owned properties

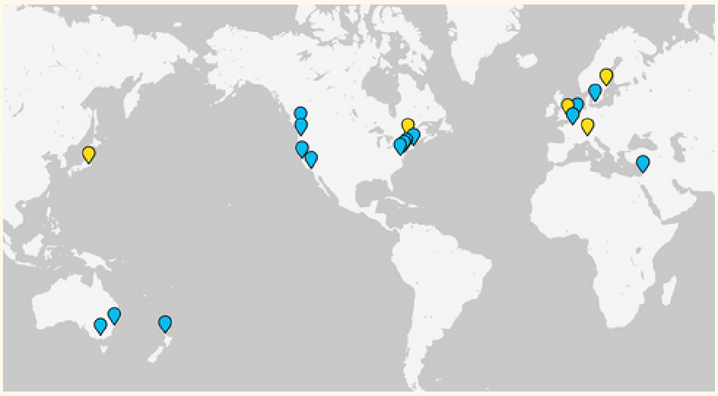


FIGURE 1: C40 ZERO WASTE SIGNATORY CITIES (CREDIT: C40.ORG)

CREDIT: MAK/GEORG MAYER/EOOS NEXT

Key Definitions

- **Urine diversion** – separation of urine from other wastewater for nutrient recovery
- **Circularity** – a concept for systems aiming to eliminate waste and virgin material use by reusing materials from waste
- **Wastewater Treatment Plant (WWTP)** – municipal system used to sanitize wastewater before returning it to the environment
- **Nitrogen (N)** – renewable element found in the atmosphere; extracted from the atmosphere to create fertilizers
- **Phosphorus (P)** – finite element found in rocks; mined to make fertilizers
- **Planetary boundaries** – concept defined by Rockström et al. (2009) quantifying nine global limits such as climate change, biodiversity loss, and land use that define the safe space for humanity; crossing them may create large and/or irreversible changes to an inhospitable environment
- **Eutrophication** – a process triggered by excess nutrients (N and P) in waters causing algal blooms which eventually reduce the oxygen in the water, killing fish and other aquatic life and creating dead zones (NOAA, 2022)

CONTEXT

Human activity is pushing the safe boundaries of the planet in multiple facets, and one boundary that is critical yet underrecognized is biogeochemical flows, specifically nitrogen and phosphorus (Rockström et al., 2009). These nutrients have natural cycles and are critical to the growth of plants, including crops. Humans have been using fertilizers since the beginning of agriculture; however, since the invention of synthetic fertilizers, humans have multiplied use of phosphorus and nitrogen. Phosphorus (P) is a non-renewable element mined from rock, while nitrogen (N) is in atmosphere in its inert form and is extracted from the air using fossil fuels. The major increase in the circulation of these nutrients is damaging other parts of the biosphere. Fertilizer runoff, human sewage, and animal manure all containing N and P wash into rivers and coastal waters and cause eutrophication, killing aquatic life (Mayer et al., 2016; Rockström et al., 2009).

If the world were to immediately cease crossing planetary boundaries such as N and P flows, there would only be enough resources to feed about 3 billion people; however, feeding up to 10 billion people is possible if agriculture is systematically optimized, including the manufacture and application of fertilizers (Gerten et al., 2020). Thus, society needs to rediscover what our microbial ancestors discovered billions of years ago that allowed their populations to flourish in limited environments: waste recycling (Lenton and Watson, 2011).

Human waste, specifically urine, is rich in P and N. Less than 1% of wastewater by volume is urine, but urine contains between 50 and 80% of the N and P in wastewater (Figure 3) (Pathy et al., 2021). Scientists estimate that recovering all N and P in urine could supply 14-19% and 7-22% respectively of the global demand for these elements, reducing the need for extraction (Martin et al., 2022; Mihelcic et al., 2011; Qadir et al., 2020). These elements are supposed be filtered out and disposed of in existing wastewater treatment plants (WWTPs) due to water quality regulations, but not very effectively: globally, sewage adds about 6 Tg of N yearly to the ocean,

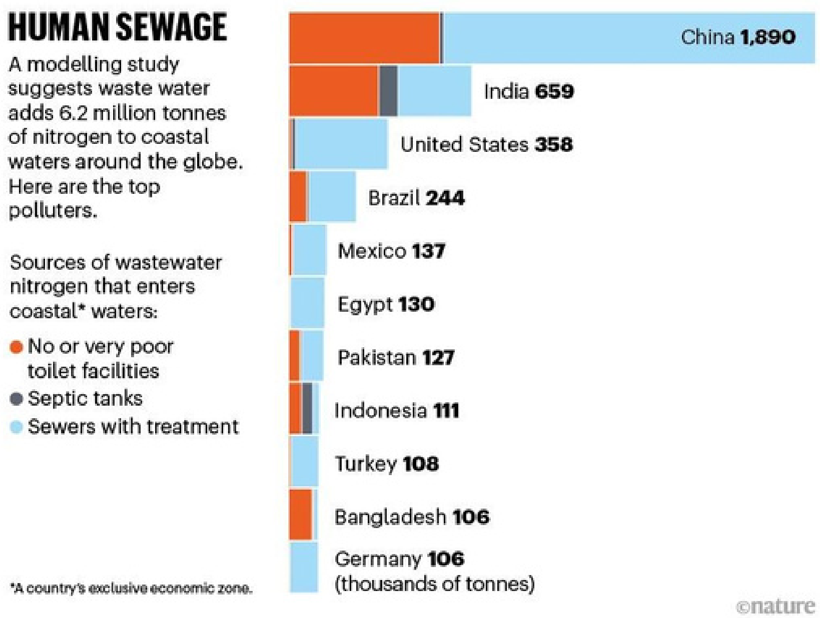


FIGURE 2: SEWAGE CONTRIBUTIONS TO NITROGEN POLLUTION (TUHOLSKE ET AL., 2021; IMAGE CREDIT WALD, 2022)

63% of which is from sewered systems (Figure 2) (Tuholske et al., 2021). Urine as a fertilizer has been tested in numerous trials in different contexts, from low to high resource settings, and it performs as well or better than synthetic fertilizer depending on the application method (Kundu et al., 2022).

Society should become more circular and reuse what is currently defined as waste rather than extracting more raw materials from the environment (Figure 4). Currently, the 27 signatory cities of the C40 Towards Zero Waste accelerator (Figure 1) have committed to reducing solid waste generation and landfilling, but wastewater is not addressed (Zeller et al., 2022). Cities are in a powerful position to address this challenge as waste management and water treatment are services they provide.

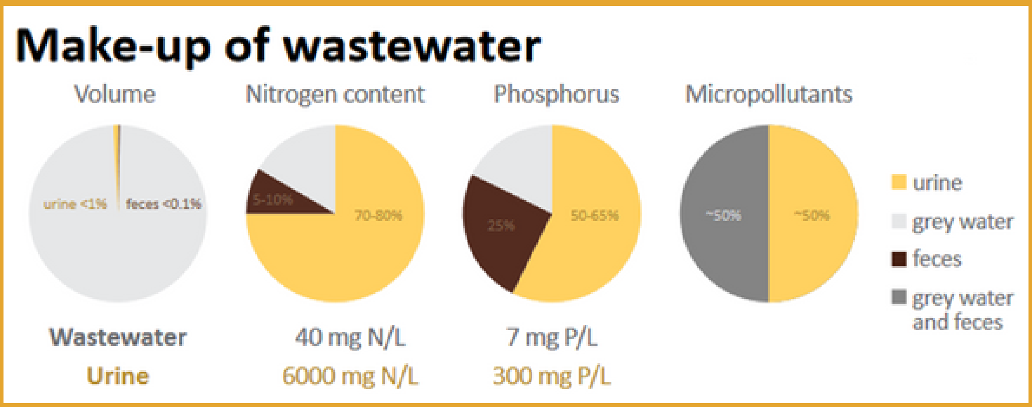


FIGURE 3: URINE CONTAINS THE MAJORITY OF NUTRIENTS IN WASTEWATER (ATLEE ET AL., 2019)

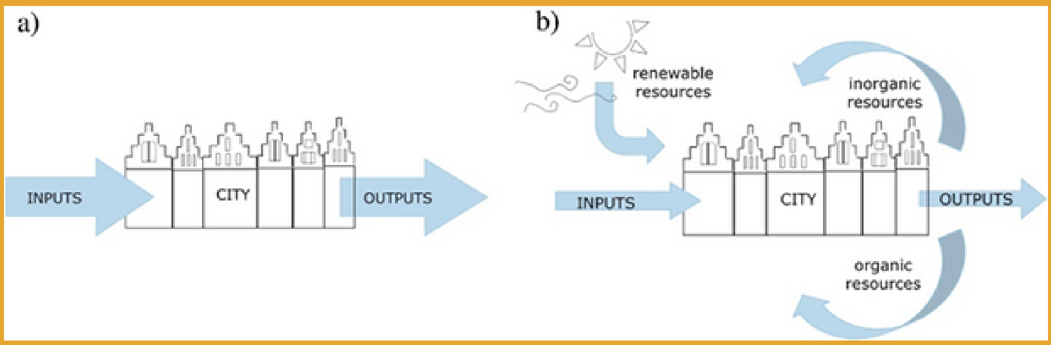


FIGURE 4: CITIES CAN BECOME PARTIALLY SELF-SUFFICIENT BY REUSING AND RECYCLING RESOURCES (WIELEMAKER ET AL., 2018)

THE CHALLENGE

There are several lock-ins that prevent swiftly moving to nutrient recovery. First, the physical infrastructure of WWTPs is incompatible and is expensive to revamp (Barquet et al., 2020; Larsen, 2020). This is because single stream sewage cannot effectively recover the diluted nutrients; additionally, urine is largely free of pathogens, but mixing it with feces introduces pathogens that cannot be spread on crops (Martin et al., 2022). The second major barrier is the low cost of synthetic fertilizers by excluding negative environmental effects, making it unlikely that any urine-based fertilizer would be profitable on the open market (Mayer et al., 2016). Next, unmetabolized pharmaceuticals are excreted through urine, leading to concerns about application to crops (Martin et al., 2020). Finally, there is a cultural taboo to urine in many societies (Atlee et al., 2019).

Each of these issues can be addressed. First, multiple surveys in the EU and US, where many of the Zero Waste cities are located, have shown that most people were accepting of the idea, and some were even willing to pay more to facilitate it. Additionally, animal waste is already widely used and accepted as a fertilizer (Kundu et al., 2022).

Safety is an important concern, but implementation of urine-diverting toilets (Figure 5) effectively separates urine from most pathogens in feces. Moreover, converting to fertilizer sterilizes it, even in low-tech methods such as long-term storage where the ammonia kills bacteria (Atlee et al., 2019). Pharmaceutical contamination is not a barrier because charcoal or biochar filtration can effectively remove traces of pharmaceuticals (Martin et al., 2022). Furthermore, WWTPs do not remove all traces of drugs and leak pharmaceuticals to the environment. Pharmaceutical pollution is significantly detrimental to aquatic species (Gros et al., 2010); thus, capturing and filtering the urine would improve on the status quo.

Concerning economic feasibility, WWT is a necessary public health service and is currently unprofitable (Otoo et al., 2015). However, with the finite natural P available, future increases in fertilizer prices may

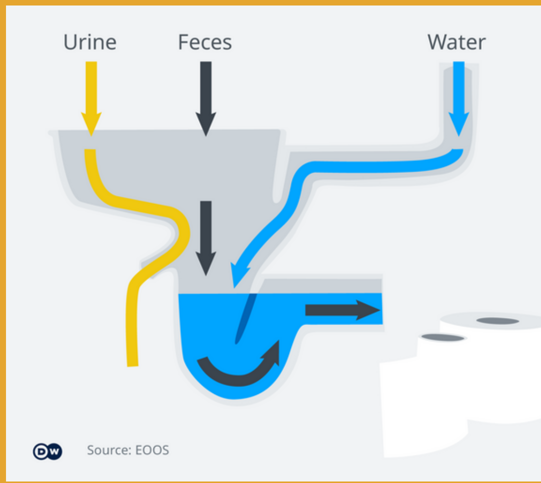


FIGURE 5: URINE DIVERTING FLUSH TOILET (CREDIT: EOOS)

CREDIT: FERENCZ ISTVAN / PEXELS

RECOVERING ALL N AND P IN URINE COULD SUPPLY 14-19% AND 7-22% RESPECTIVELY OF THE GLOBAL DEMAND

CREDIT: TETIANA NEKRASOVA / CAPTURENOW

change this. Plus, urine-based fertilizer could tap into the organic market (Figure 7) which is valued at more than USD 8 billion globally and is projected to grow 6% annually (Karak and Bhattacharyya, 2011; Yamini and Eswara, 2021). Another economic benefit is that urine diversion can extend the life of WWTPs by reducing nutrient loads, especially P which precipitates in piping leading to blockages. Urine diversion can save hundreds of thousands of dollars per year in maintenance (Mayer et al., 2016). An alternative WWT system could cost USD 260 to 680 per person and remain cost competitive with current systems (Maurer et al., 2005).

Urine diversion has important environmental benefits. Lifecycle assessments of modeled cities in Virginia, Michigan, and Vermont showed reduction of 29-47% in greenhouse gas emissions, 50% in freshwater use, 26-41% in energy use, and 25-64% in eutrophication (Hilton et al., 2021). This is in part due to the replacement of synthetic fertilizer, but an analysis of WWTPs in China showed that the biochemical treatment made up 50-70% of the process energy demand which would also be reduced by diverting urine (Li et al., 2017). The biggest environmental benefit is the decrease in nutrients discharged to surface waters, which helps cities comply with national or international regulations limiting nutrients discharged to waters and reduces eutrophication (Barquet et al., 2020).

Finally, urine diversion contributes to food security and urban circularity. One study showed that Rotterdam (Netherlands, population 620,000) could farm its available arable land and rooftops and fertilize it with recovered nutrients to completely supply the city's produce needs. Urine diversion could meet 100% of P needs and partial N needs [1] (Wielemaker et al., 2018).

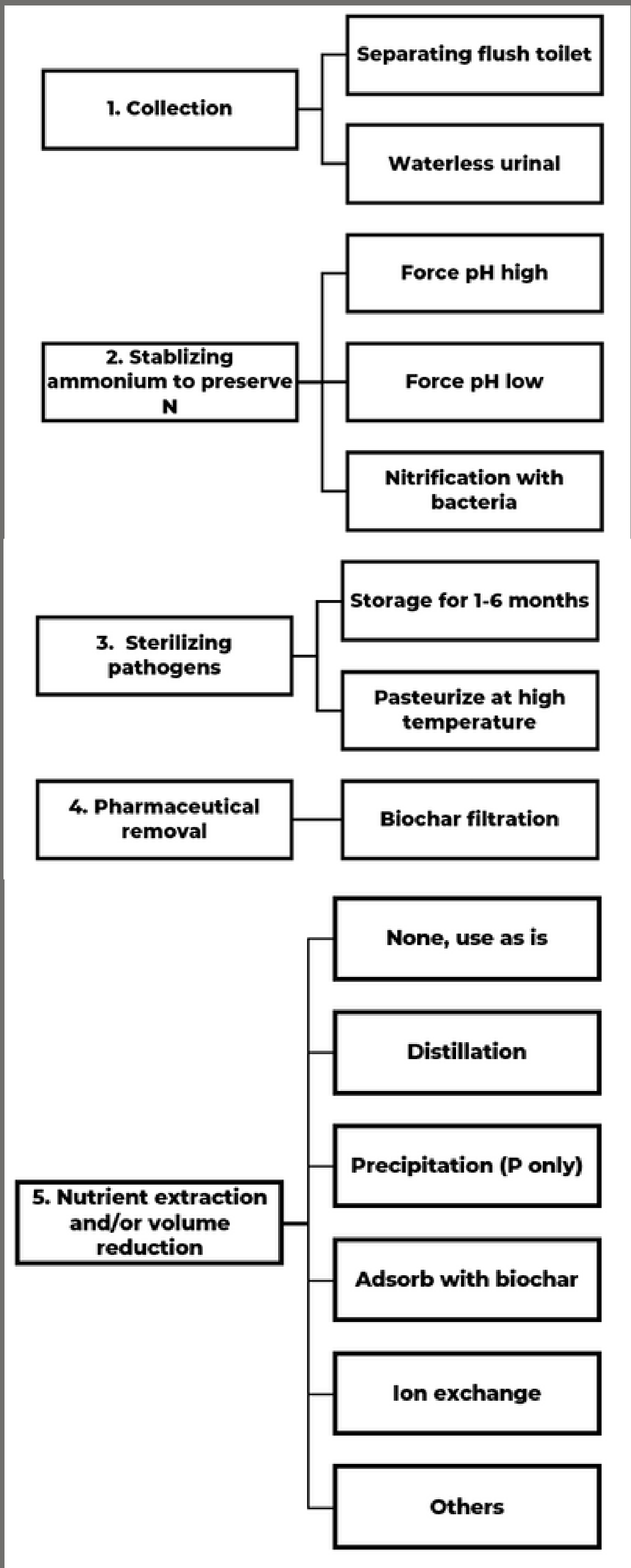


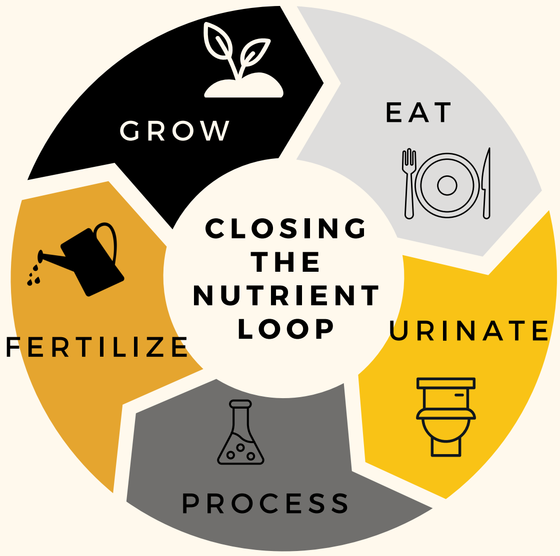
FIGURE 6: A SELECTION OF TECHNICAL METHODS FOR EACH CHALLENGE IN NUTRIENT RECOVERY SUMMARIZED FROM KUNDU ET AL. (2022)

[1] The ratio of N:P in urine versus the ratio needed by plants means it is impossible to use only urine without over-applying P (Barquet et al., 2020)

C40 CITIES

POLICY RECOMMENDATIONS

FOR C40 ZERO WASTE CITIES



Meadows' (2008) theoretical leverage points in a system were used to develop and prioritize these recommendations. The full list can be found in Further Reading.

1. Shift purpose of wastewater system to recovery rather than treatment

First, explicitly shifting the purpose of the wastewater system to recovery rather than treatment will frame the upcoming discussions of physical infrastructure and policy changes. Working towards circularity will necessitate changes in the wastewater system to achieve it and aligns with C40 Zero Waste cities' goals.

2. Direct city actions: build urine processing and transportation infrastructure and retrofit municipal buildings

If purpose shift and community involvement are given, then the first thing that must change is the physical infrastructure of the wastewater system for urine. Cities are usually the owners, operators, and/or financiers of their WWTP, thus deciding to use a new technology is within their remit. Depending

INVOLVE CITIZENS

Whichever technical urine diversion option is chosen, community participation in the decision is necessary to overcome social taboos and ensure suitability and buy in for all players, from donors and plumbers to farmers and regulators. Though recommending a specific policy for educating and collaborating with the public is beyond the scope of this brief, it is necessary for a successful implementation.

FIGURE 7: VUNA IS A SWISS COMPANY THAT INSTALLS SMALL SCALE URINE RECOVERY SYSTEMS AND PRODUCES AURIN, THE FIRST HUMAN URINE-BASED FERTILIZER (VUNA, N.D.)

on the urine diversion method (Figure 6, 8), the centralized infrastructure may be a sterilization or fertilizer production facility as well as a transportation method for the urine. To avoid the high cost of re-piping a city, trucks can be used for transportation [1] (Chipako and Randall, 2020). The transportation and/or the nutrient recovery could be outsourced as well. Finally, cities should retrofit the buildings they own with urine diverting toilets and collection infrastructure such as storage tanks or piping.

3. Indirect city actions: policy to increase adoption

For changes in buildings beyond what the city directly owns and operates, specific policies are needed. Following the example of energy and water efficiency standards which have been proven to be effective in reducing consumption (Boza-Kiss et al., 2013), municipal governments should introduce nutrient circularity standards, especially for high-capacity buildings such as stadiums, office buildings, shopping centers, and large apartment buildings. Additionally, building codes, which also have a track record of creating energy savings worldwide, can be utilized to require diversion infrastructure in new builds (Navarro Martínez et al., 2022). Eventually, mandating retrofitting of existing buildings or as a requirement in renovation permitting should be added. Though this may come at a significant cost depending on the technological solution chosen, initial adopters could be subsidized as solar power and electric vehicle early adopters were. This can catalyze widespread use and close the nutrient loop.

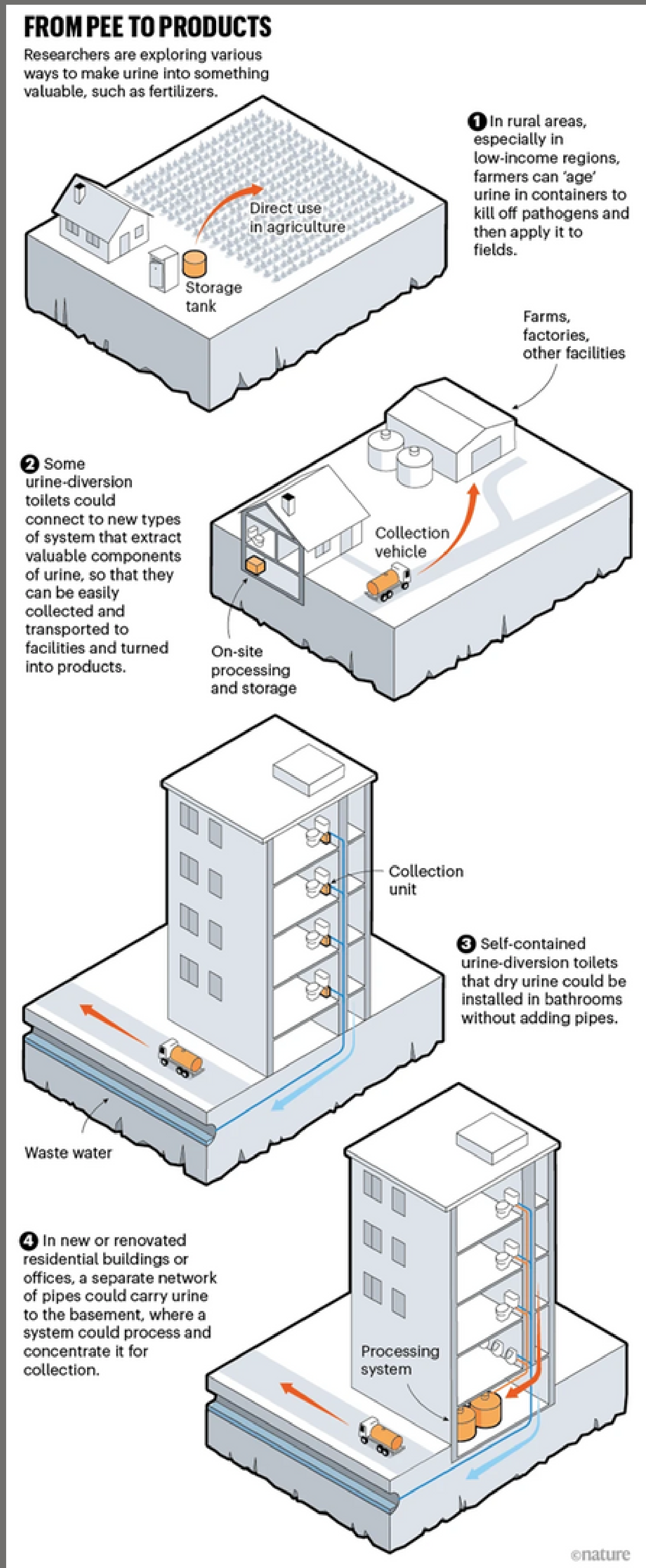


FIGURE 8: POTENTIAL SYSTEMS FOR URINE DIVERSION (WALD, 2022)

[1] Using trucks can still save emissions when optimized (Chipako and Randall, 2020)

FURTHER READING

- The Rich Earth Institute in Vermont, USA: fully decentralized system in rural area with direct application as fertilizer http://richearthinstitute.org/
- Eawag – Swiss Federal Institute of Aquatic Science and Technology: several projects in South Africa, Nepal, space, and Switzerland https://www.eawag.ch/en/department/eng/projects/
- Donella Meadows' (2008) Thinking in Systems, Chapter 6: Leverage Points - Places to Intervene in a System
- Kundu et al. (2022) summarizes the current state of technology

CREDIT: TRASHHAND / PEXELS

REFERENCES

Atlee, J., Noe-Hays, A., Nace, K., Schreiber, T., Davis, A., Lally, C., and Dotson, S. (2019) *Guide to Starting a Community-scale Urine Diversion Program*.

Barquet, K., Järnberg, L., Rosemarin, A., and Macura, B. (2020) Identifying barriers and opportunities for a circular phosphorus economy in the Baltic Sea region. *Water Research* 171: 115433.

Boza-Kiss, B., Moles-Grueso, S., and Urge-Vorsatz, D. (2013) Evaluating policy instruments to foster energy efficiency for the sustainable transformation of buildings. *Current Opinion in Environmental Sustainability* 5(2): 163–176.

Chipako, T. L., and Randall, D. G. (2020) Investigating the feasibility and logistics of a decentralized urine treatment and resource recovery system. *Journal of Water Process Engineering* 37: 101383.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., and Schellnhuber, H. J. (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability* 2020 3:3 3(3): 200–208.

Gros, M., Petrović, M., Ginebreda, A., and Barceló, D. (2010) Removal of pharmaceuticals during wastewater treatment and environmental risk assessment using hazard indexes. *Environment international* 36(1): 15–26.

Hilton, S. P., Keoleian, G. A., Daigger, G. T., Zhou, B., and Love, N. G. (2021) Life Cycle Assessment of Urine Diversion and Conversion to Fertilizer Products at the City Scale. *Environmental Science and Technology* 55(1): 593–603.

Karak, T., and Bhattacharyya, P. (2011) Human urine as a source of alternative natural fertilizer in agriculture: A flight of fancy or an achievable reality. *Resources, Conservation and Recycling* 55(4): 400–408.

Kundu, S., Pramanik, B. K., Halder, P., Patel, S., Ramezani, M., Khairul, M. A., Marzbali, M. H., Paz-Ferreiro, J., Crosher, S., Short, G., Surapaneni, A., Bergmann, D., and Shah, K. (2022) Source and central level recovery of nutrients from urine and wastewater: A state-of-art on nutrients mapping and potential technological solutions. *Journal of Environmental Chemical Engineering* 10(2): 107146.

Larsen, T. A. (2020) Urine Source Separation for Global Nutrient Management. In *Women In Engineering and Science*. Springer.

Lenton, T., and Watson, A. (2011) Playing Gaia. In *Revolutions That Made the Earth* (1st ed.). Oxford University Press.

Li, W., Li, L., and Qiu, G. (2017) Energy consumption and economic cost of typical wastewater treatment systems in Shenzhen, China. *Journal of Cleaner Production* 163: S374–S378.

Martin, T. M. P., Esculier, F., Levavasseur, F., and Houot, S. (2022) Human urine-based fertilizers: A review. *Critical Reviews in Environmental Science and Technology* 52(6): 890–936.

Maurer, M., Rothenberger, O., and Larsen, T. A. (2005) Decentralised wastewater treatment technologies from a national perspective: at what cost are they competitive? *Water Supply* 5(6): 145–154.

Mayer, B. K., Baker, L. A., Boyer, T. H., Drechsel, P., Gifford, M., Hanjra, M. A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., and Rittmann, B. E. (2016) Total Value of Phosphorus Recovery. *Environmental Science and Technology* 50(13): 6606–6620.

Meadows, D. (2008) Leverage Points - Places to Intervene in a System. In Wright, D. (Ed.), *Thinking in Systems*. Chelsea Green Publishing.

Mihelcic, J. R., Fry, L. M., and Shaw, R. (2011) Global potential of phosphorus recovery from human urine and feces. *Chemosphere* 84(6): 832–839.

Navarro Martínez, I. J., Sánchez-Garrido, A. J., Akram, M. W., Firdaus, M., Zublie, M., Hasanuzzaman, M., and Rahim, N. A. (2022) Global Prospects, Advance Technologies and Policies of Energy-Saving and Sustainable Building Systems: A Review. *Sustainability* 2022, Vol. 14, Page 1316 14(3): 1316.

NOAA (11/09/2022) What is eutrophication? *National Oceanic and Atmospheric Administration*. Accessed: 4th December 2022 <https://oceanservice.noaa.gov/facts/eutrophication.html. >.

Otoo, M., Drechsel, P., and Hanjra, M. A. (2015) Business models and economic approaches for nutrient recovery from wastewater and fecal sludge. *Wastewater: Economic Asset in an Urbanizing World* : 247–268. doi:10.1007/978-94-017-9545-6_13/TABLES/2.

Pathy, A., Ray, J., and Paramasivan, B. (2021) Challenges and opportunities of nutrient recovery from human urine using biochar for fertilizer applications. *Journal of Cleaner Production* 304: 127019.

Qadir, M., Drechsel, P., Jiménez Cisneros, B., Kim, Y., Pramanik, A., Mehta, P., and Olaniyan, O. (2020) Global and regional potential of wastewater as a water, nutrient and energy source. *Natural Resources Forum* 44(1): 40–51.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., et al. (2009) A safe operating space for humanity. *Nature* 461(7263): 472–475.

Tuholske, C., Halpern, B. S., Blasco, G., Villasenor, J. C., Frazier, M., and Caylor, K. (2021) Mapping global inputs and impacts from of human sewage in coastal ecosystems. *PLOS ONE* 16(11): e0258898.

Vuna (n.d.) Urine recycling technology. Accessed: 4th December 2022 <https://vuna.ch/en/urin-recycling-technologie/. >.

Wald, C. (2022) The urine revolution: how recycling pee could help to save the world. *Nature* 602(7896): 202–206.

Wielemaker, R. C., Weijma, J., and Zeeman, G. (2018) Harvest to harvest: Recovering nutrients with New Sanitation systems for reuse in Urban Agriculture. *Resources, Conservation and Recycling* 128: 426–437.

Yamini, P., and Eswara, P. (/11/2021) Organic Fertilizers Market Size. *Allied Market Research*. Accessed: 3rd December 2022 <https://www.alliedmarketresearch.com/organic-fertilizers-market-A14536. >.

Zeller, K., Cepeda-Marquez, R., Tofias, Z., Sutherland, C., Sadouni, I., Goff, K., Bickle, E., Dixon, N., Morel, L., Blunt, E., Samuels, D., Saville, C., Davidova, J., Hvidtfeldt, E., Diakoulakis, S., and Cuperstein, I. (2022) *C40 Advancing Towards Zero Waste Declaration: How cities are creating cleaner, healthier communities and circular economies.*