TITLE: Life-Cycle Assessment of Urine Diversion and Conversion to Fertilizer Products at the City Scale

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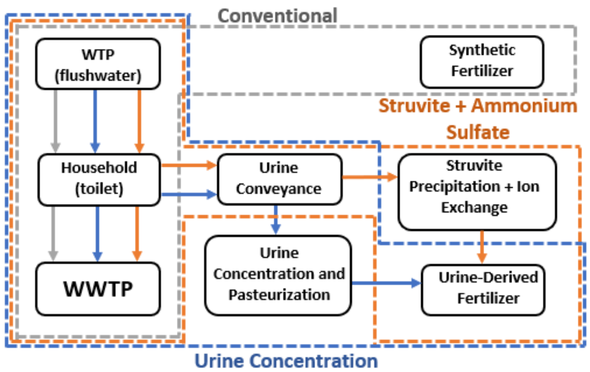
TOC Art:


Conventional
WTP (flushwater)
Synthetic Fertilizer
Struvite + Ammonium Sulfate
Household (toilet)
Urine Conveyance
Struvite Precipitation + Ion Exchange
Urine Concentration and Pasteurization
Urine-Derived Fertilizer
WWTP
Urine Concentration

ABSTRACT

Urine diversion has been proposed as an approach for producing renewable fertilizers and reducing nutrient loads to wastewater treatment plants. Life cycle assessment was used to compare environmental impacts of the operations phase of urine diversion and fertilizer processing systems (via 1) a urine concentration alternative and 2) a struvite precipitation and ion exchange alternative) at a city scale to conventional systems. Scenarios in Vermont, Michigan, and Virginia were modeled, along with additional sensitivity analysis to understand the importance of key parameters, such as the electricity grid and wastewater treatment method. Both urine diversion technologies had better environmental performance than the conventional system, and led to reductions of 29-47% in greenhouse gas emissions, 26-41% in energy consumption, approximately half the freshwater consumption, and 25-64% in eutrophication, while acidification ranged between a 24% decrease to a 90% increase. In some situations wastewater treatment chemical requirements were eliminated. The environmental performance improvement was usually dependent on offsetting the production of synthetic fertilizers. This study suggests that urine diversion could be applied broadly as a strategy for both improving wastewater management and decarbonization.

INTRODUCTION

About half of the world food supply depends on synthetic fertilizers produced from nonrenewable resources [1].Phosphate rock is used to produce phosphorus fertilizers. While the extent of the resource base is contested, supply is finite, demand has increased partly due to increased meat consumption and biofuel production, and supplies are dominated by a few countries. [2–5] Production of nitrogen fertilizer depends on natural gas, and is responsible for about 1.2% of world energy use and associated greenhouse gas emissions. [6,7] Prices for phosphate rock and other fertilizer commodities have fluctuated as much as 800% in recent years, which has led to food riots in many countries.[3,4,8] Given the impacts and resource constraints of conventional fertilizers, renewable and reliable alternatives are needed.

Food consumption by humans is the principal source of these vital nutrients in domestic wastewater, and significant resources are invested to remove them to protect the aquatic environment. Water and wastewater systems consume about 3-4% of the total electricity in the United States, with nutrient removal often being one of the most energy intensive processes.[9,10] Some propose separately collecting urine and using it to produce fertilizer.[11,12] Although it comprises less than 1% of wastewater volume, urine contains approximately 50% of the phosphorus and 80% of the nitrogen contained in domestic wastewater. [13–15] As utilities increasingly focus on sustainability, large-scale urine diversion has the potential to improve regional wastewater management, recover essential resources and reduce energy consumed in processes such as aeration. [11,16–19]

Compared to synthetic fertilizers, urine-derived fertilizers recover important nutrients, can be as effective at stimulating plant growth, and contain lower levels of heavy metals. [19–26] However, processing fertilizers from urine will have environmental impacts. [15] Collecting and transporting urine will require new infrastructure systems, such as pressurized pipe networks or truck collection.

Use of acetic acid or other chemicals may be needed to prevent the spontaneous release of ammonia gas and formation of precipitates that clog piping infrastructure. [15,27–29] Urine concentration, through processes such as reverse osmosis, freeze thaw, or distillation, may be required to make nutrient concentrations in urine, which are much lower than synthetic fertilizer, high enough for efficient agricultural application. [15,30–34] Alternatively, nutrients may be concentrated through removal processes such as struvite precipitation, ammonia capture via ion exchange, or urea adsorption. [15,20,35–41] Additional treatment to deactivate pathogens and remove pharmaceuticals found in urine may also be needed.[25,42,43]

Life Cycle Assessment (LCA) is well suited to compare the environmental performance of urine diverting systems to conventional systems, determine environmental hotspots, and highlight trade-offs and opportunities for system improvement.[44,45] LCA has been used to compare a range of wastewater treatment alternatives, [46–50] and in most cases has indicated that urine diversion has lower environmental impacts than conventional systems. [13,14,51–58] However, these studies have focused on small scale systems, have evaluated only a few locations and urine-derived fertilizers, and simplified how diverting urine will affect wastewater treatment plants. These studies measure changes to wastewater through volume reduction or a static offset for denitrification, which may not capture significant changes to wastewater treatment as nutrient ratios change, or how urine diversion could change treatment configurations.[51,52,59–61]

This study expands upon previous research by evaluating the environmental impacts of urine diversion and conversion to fertilizer relative to conventional alternatives in large and diverse settings,[57,62] and by a more detailed assessment of how this will affect wastewater treatment. This conventional alternative manages urine through the wastewater system and produces and transports equivalent amounts of nutrients in the form of synthetic fertilizer. The relative differences between these two different approaches are quantified. Wastewater treatment is modeled in detail to better account for the ramifications of urine diversion. Three distinct locations, namely the States of Vermont, Michigan, and Virginia (referred to subsequently as scenarios) are considered to explore how important parameters such as population, extent of nutrient removal at wastewater treatment plants, electricity grid fuel mix and the amount of urine-derived fertilizer produced influence the environmental performance. Sensitivity analysis is conducted using Monte Carlo in order to further evaluate these parameters and the uncertainty of many others.

METHODS AND MATERIALS

Urine Processing Alternatives

Two distinct urine-derived fertilizer alternatives were evaluated to represent the range of products that can be produced. They consist of (1) concentrated urine, where organics such as pharmaceuticals are removed from diverted urine through activated carbon and urine is subsequently concentrated by reverse osmosis (RO) and then heat pasteurized, and (2) struvite and ammonium sulfate, where urine is processed to produce struvite through precipitation and ammonium sulfate through ion exchange. Use of urine-derived fertilizer products are compared to commercial fertilizers. For the urine-derived fertilizer alternatives it was assumed that 70 percent of urine in each of the three scenarios (Vermont, Michigan, and Virginia) considered was diverted for fertilizer production.[63] This was done to simulate large-scale collection within these locations but to allow for some inefficiency in collection. As shown in Figure 1, production and distribution of flushwater, collection of wastewater (including separated urine), production and transportation of fertilizers, and wastewater treatment were included in the scope of the study to capture system-wide differences. More information on these alternatives can be found below and in section 3 in the supplemental information.

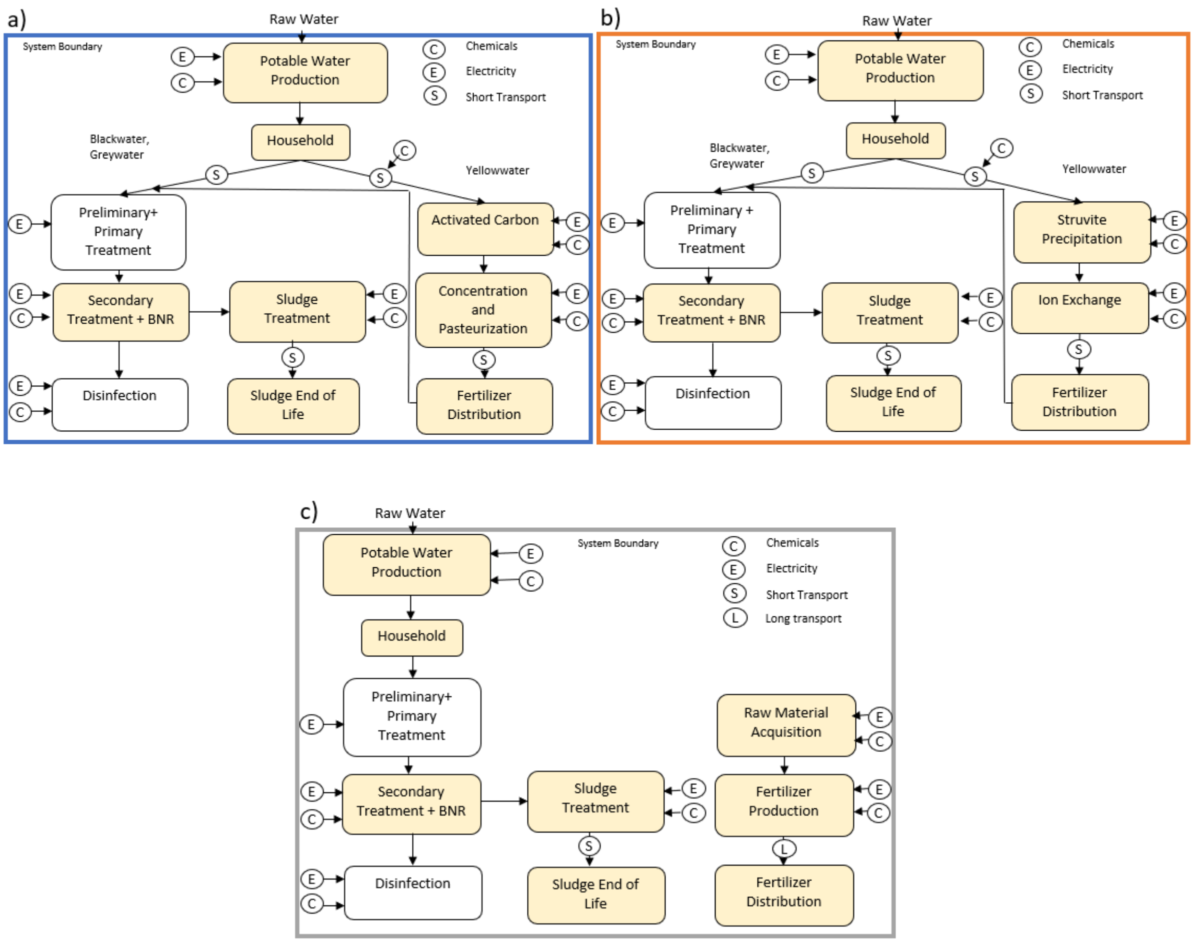


Figure 1 a-c. System Diagram for each alternative.

a) The urine concentration alternative, b) the struvite and ammonium sulfate alternative, c) the conventional system. Yellow boxes indicate that a process is either unique to that alternative, or that urine diversion significantly affects its environmental impact.

The inputs to treat and distribute flush water were determined using the ratio of surface and groundwater treated in each location,[64] and literature data for both types of treatment. [51,65–76] When urine was diverted, urine diversion toilet flush volumes were used. In the conventional alternative, for people not using urine-diverting toilets, and during defecation, low-flow toilet flush volumes were used, as shown in Tables S6 & S7. When urine is diverted, acetic acid is added to stabilize it, followed by transportation to a fertilizer production center via a pressurized pipe system.

Magnesium oxide is added to precipitate phosphorus as struvite and the remaining ammonium from the effluent is captured through ion exchange using a resin such as Dowex Mac 3.[39] The exhausted resin is regenerated with 3 M sulfuric acid, producing a liquid ammonium sulfate fertilizer. Additional acetic acid is needed for the concentrated urine fertilizer to consistently maintain nitrogen in the urea form. Following pharmaceutical removal using activated carbon sized for pharmaceutical removal, urine is concentrated to a fifth of its original volume using reverse osmosis with an energy recovery device (ERD) and then heat pasteurized. Chemical and energy inputs for regeneration of activated carbon[77–81] and reverse osmosis membrane cleanings[82] are included. Effluents from the urine-derived fertilizer production facilities are sent to the wastewater treatment plant, and the urine-derived fertilizers are trucked to a regional fertilizer distributor.

The methodology described in Hilton et al.[83] is used to model wastewater treatment for all alternatives to determine electricity consumption, chemical consumption, secondary sludge production, water and air emissions. All alternatives assumed equal amounts of feces and greywater, steady state conditions, and compliance with all regulatory requirements. Processes that were unaffected by urine diversion, such as primary sludge treatment and hauling screenings to landfills, were excluded. Further details can be found in the supplemental materials, Figure S1, and Hilton et al.[83]

The production of urea and mono-ammonium phosphate fertilizers and transportation to the regional fertilizer distribution center was used to ensure all alternatives provided the same mass of nitrogen and phosphorus as fertilizer. These synthetic fertilizers were added in the conventional and both diversion alternatives to provide equal amounts of nitrogen and phosphorus despite differing nutrient recovery ratios. Transportation from the regional fertilizer distribution center and application at the farm were not analyzed, as previous research did not find plant uptake and runoff from urine-derived fertilizers to differ from synthetic fertilizers.[25,84–86]

Life Cycle Assessment

The treatment of one person equivalent's (p.e.) wastewater for one year is the functional unit of analysis used. Treatment of all wastewater produced (including urine as appropriate) is considered because urine diversion can lead to significant reductions in the nitrogen and phosphorus of wastewater arriving at the treatment plant, and can significantly affect treatment. All alternatives provided equal masses of nitrogen and phosphorus in fertilizer. Environmental burdens of capital equipment and the end of life of wastewater and fertilizer infrastructure were excluded because the operational phase impacts are expected to dominate. [87–91]

Parameters used for the life cycle inventory and mass balance were obtained from literature sources and pilot scale systems, and can be found in Tables 1, S6 and S8. The United States Life Cycle Inventory (USLCI) was used for most unit processes, though Ecoinvent was used when unit processes were not available.[92,93] A Life Cycle Impact Assessment was conducted using global warming potential (GWP), cumulative energy demand (CED), freshwater use,[94] eutrophication potential (EP), and acidification potential (AP). Global Warming Potential was calculated using GWP 100a from the Fifth Assessment Report,[95] and the TRACI 2.0 methodology is used for eutrophication and acidification potential.[96] These categories represent key impacts for changes in energy use, chemical manufacturing, water quality, and water use that are caused by urine diversion.

Table 1. List of important inputs used to model urine collection and fertilizer production. C is short for conventional, SAS is short for struvite and ammonium sulfate and UC is short for urine concentration.

Process	Parameter	Value	Unit	Notes and Sources

Home/Collection	Flushes per person per day	3.8,5.14	/pe · day	Urine only, then total[97–102]
	C water per flush	4.84	L/flush	Also used for feces flushes in UD toilets
	SAS & UC: water per flush	0.165	L/flush	Used for urine-only flushes.[18,103]
	5% acetic acid added	0.033-0.04	L/L urine and flushwater	SAS (Calculated) then UC (Experimentally determined [25])
SAS Production	Mg:P ratio for struvite	1.5:1		[51,61,104,105]
	Sulfuric acid per kg N	16.7	liters/kg N	18%. Tarpeh, personal conversation.

	N and P recovery	96, 96	%	[39,51,61,106,107]
UC Production	RO electricity consumption	0.009	kWh/l removed	Noe-Hays, Personal Communication
	N & P Recovery	95, 99	%	[108,109]

Description of Scenarios Evaluated

Three scenarios were modeled to provide an initial assessment of how location-specific factors affect the environmental merits and drawbacks of urine diversion. The Vermont scenario represents a smaller urban community without strict nitrogen effluent limits located in a largely rural state. The Michigan scenario was developed as a statewide average and was constructed by categorizing the range of communities in the State, the types of wastewater treatment plants found, and wastewater treatment volumes. The Virginia scenario represents a more densely-populated urban location with strict effluent limits. Hypothetical scenarios were modeled based on these treatment plants where the wastewater was assumed to be predominately comprised of domestic and commercial wastewater. Further description of these scenarios can be found in the supplemental materials, Tables 2 and S9-S15, and Hilton et al. [83] All alternatives were evaluated for each scenario.

Table 2. Summary Comparison of Three Scenarios Considered

Item	Vermont	Michigan	Virginia

Description	Largely rural state with small to mid-size communities	Large state with diverse range of community sizes	Stringent effluent discharge standards
Population Modeled	25,000	150,000	350,000
Hydraulic Capacity (m^3/day)	85,000	32,000-3,500,000	205,000
Effluent Discharge Standards	Secondary, P limits	Secondary, P, some ammonia and TN limits	Advanced Secondary, stringent TN and P limits
Effluent Total Nitrogen limits (mg/L)	None	Variable	4
Effluent Phosphorus Limits (mg/L)	0.2	0.7	0.18
Wastewater Treatment Process(es)[110]	Single Aeration Basin	Single Aeration Basin, Nitrification, A2O	5-Stage Bardenpho
Typical Distance to Fertilizer Distributors (km)	28	18	63
GWP of Electricity (kg CO_2e/kWh)	0.107	0.544	0.450

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the results, test urine diversion in a broader range of contexts, and to elucidate how model parameters and key assumptions influenced the environmental performance of urine diversion. Twelve separate simulation scenarios were created. As shown in Figure S2, six of these simulation scenarios modeled the 5-Stage Bardenpho treatment plant because it had the highest level of nutrient removal, while six modeled the single aeration basin with phosphorus removal because it had the lowest level of nutrient removal. Three electric grids, coal, natural gas, and renewable comprised of 50% wind and 50% hydropower were considered for each wastewater treatment type. Both the urine concentration, and struvite and ammonium sulfate urine derived fertilizer alternatives were compared, given six simulations for each wastewater treatment type. Table S16 lists the distributions of each parameter used. The Excel plugin Simvoi was used to conduct a Monte Carlo analysis with 10,000 repetitions for each sensitivity scenario[111].

RESULTS

Life Cycle Impacts Across Scenarios

Urine diversion consistently provides improved environmental performance relative to the conventional system for each scenario for all impact categories, except acidification potential, as shown in Table 3. Both diversion alternatives reduced the global warming potential, cumulative energy demand, freshwater use, and eutrophication potential categories from anywhere between 24% to 63%. The urine concentration alternative typically led to larger improvements than the struvite and ammonium sulfate alternative. Urine concentration alternatives decreased the acidification potential modestly compared to the conventional alternative for all scenarios (9-22%), while struvite and ammonium sulfate alternatives increased the acidification potential by 34% to 91% relative to the conventional alternative. Figures 2, and S17 provide the relative differences in environmental performance for each alternative.

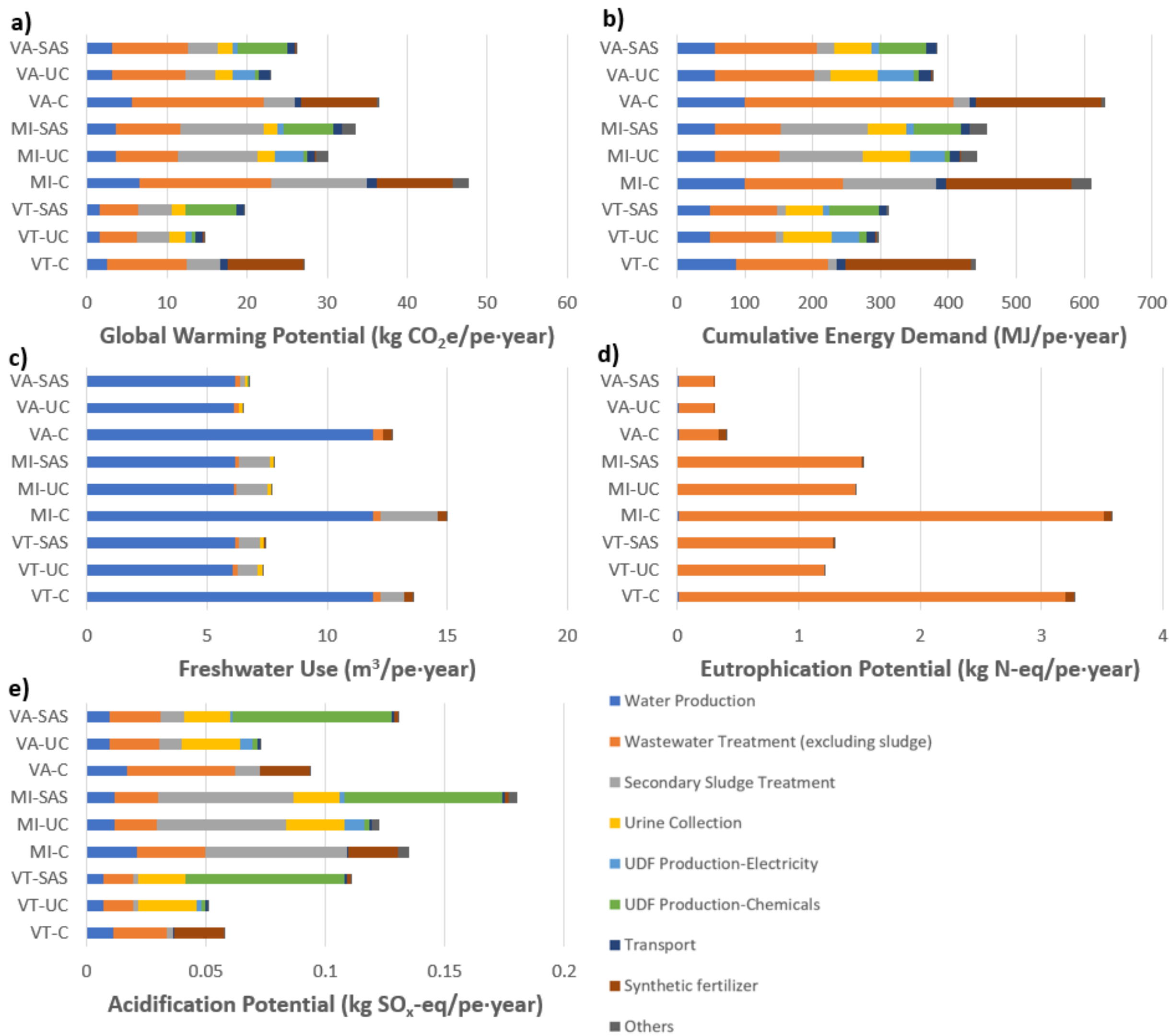


Figure 2. Total impacts in each scenario and alternative by process per capita per year. VA is short for Virginia, MI is short for Michigan, and VT is short for Vermont. SAS is short for struvite and ammonium sulfate, UC is short for urine concentration, and C is short for conventional.

The magnitude of environmental impacts differed substantially between the three scenarios. Michigan had the highest global warming potential, cumulative energy demand, and acidification potential impacts, while Vermont had the lowest. Much of this is because Michigan's electricity grid is comprised primarily of fossil fuels and uses natural gas to thermally dry sludge, while Vermont's electricity grid is mostly comprised of renewable energy sources. The Vermont scenario had an eutrophication potential approximately four times larger than in Virginia as a result of the large differences in effluent standards.

The urine diversion alternatives in states with less stringent effluent standards (Vermont and Michigan) saw the largest decreases in eutrophication potential. The differences between the urine concentration, and struvite and ammonium sulfate alternatives were smaller for scenarios where the environmental impacts of producing electricity were larger, such as in Michigan.

Life Cycle Impacts by Process

Figure 2 shows the contribution of system components to each environmental impact category. Wastewater treatment dominated the eutrophication potential (81-99%), was usually responsible for the largest proportion of impacts in global warming potential (24-45%) and cumulative energy demand (21-49%) categories, and was a major contributor to acidification potential (10-48%). Fertilizer production had the next largest impacts in the global warming potential (14-35%), cumulative energy demand (14-42%), and eutrophication potential (0-17%) categories, and was a major contributor to acidification potential (8-60%). In Michigan and Vermont, the eutrophication potential from fertilizer production was negligible relative to its contribution from wastewater effluent. Potable water production and urine collection respectively had the next largest impacts in the global warming potential and cumulative energy demand categories. The largest contributor to acidification potential was sulfuric acid (33%-49% when producing ammonium sulfate) followed by acetic acid (10-17% when producing ammonium sulfate, 35%-58% when concentrating urine).

In the conventional alternative, 10.4 cubic meters of water were needed per person per year for flushing excluding leaks between the drinking water plant and the consumer. This decreases to 5.3 cubic meters in the urine diversion alternatives, and can be as low as 3.1 cubic meters if all urine is diverted. Reduced flush volumes from urine-diverting toilets were responsible for the majority of decreased freshwater used although 6 to 21% came from upstream sources such as production of synthetic fertilizer, ferric chloride, and other chemicals.

For urine collection, producing acetic acid led to higher environmental impacts than the electricity consumed to collect urine. More acetic acid was used to ensure that urine remained stable in the urine concentration alternative. While urine diversion reduced the volume of wastewater that needed to be collected, the impacts of collecting and stabilizing urine were substantially larger than any benefits of collecting less wastewater in sewers.

Urine-derived fertilizer production resulted in about 35-73% as much global warming potential as synthetic fertilizers and decreased most other environmental impacts. The exception was AP, which ranged anywhere from an 81% decrease to a 231% increase from synthetic fertilizers. Offsetting synthetic fertilizers was almost always required to reduce global warming potential and cumulative energy demand.

The impacts of concentrating urine were dominated by electricity consumed for reverse osmosis. Unless urine diversion led to major reductions in electricity consumed at wastewater treatment plants, such as in Virginia, concentration increased total electricity within a municipality. The environmental impacts of producing concentrated urine were low in Vermont due to the high proportion of renewable energy. The impacts of producing struvite and ammonium sulfate were relatively independent of the electricity grid, with sulfuric acid being responsible for much of the global warming potential and leading to this alternative always having the largest acidification potential. Processes such as regenerating activated carbon, cleaning reverse osmosis membranes, producing magnesium oxide and ion exchange resin, and electricity for pumping in the fertilizer production facility had small overall impacts.

The global warming potential and cumulative energy demand of shipping urine-derived fertilizers to the fertilizer depot comprised a relatively small portion of the net impact, but were up to 3.5 times higher than shipping synthetic fertilizers. Synthetic fertilizers were shipped much longer distances, but only required about 4-8% as much mass, and were more likely to use larger and more efficient transports.

Urine diversion significantly decreased the impacts (global warming potential, cumulative energy demand, acidification potential) of nutrient removal from treatment plants with stringent effluent limits, whereas more lenient plants reduced the eutrophication potential of releasing effluent to aquatic ecosystems. As shown in Figure 3, all treatment plants benefitted by reducing the amount of ferric chloride required to remove phosphorus. Treatment plants with stricter effluent limits had larger reductions of electricity, methanol, and nitrous oxide emissions in biological treatment. These benefits were so large in Virginia that even if no synthetic fertilizer were offset, urine diversion would still reduce net greenhouse gas emissions. In certain cases, urine diversion could eliminate the need for ferric chloride and methanol during average conditions. Reducing total wastewater volume, capturing BOD in concentrated urine, and minor changes to secondary sludge production led to small changes in environmental impacts.

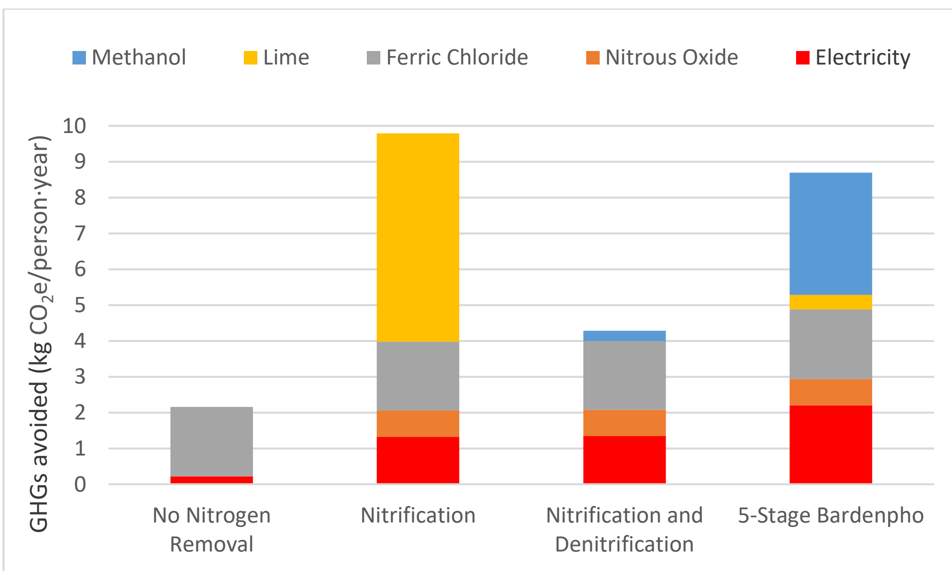


Figure 3. Greenhouse gas emissions avoided during wastewater treatment due to diverting 70% of urine. All remove phosphorus and use the Virginia electricity grid to allow comparison. The first type has an aeration basin to remove BOD (Vermont). The second category uses nitrification to oxidize ammonia to nitrate. The third category further treats wastewater with denitrification, which converts some nitrate to nitrogen gas. The final category is the 5-Stage Bardenpho treatment method which removes the most nutrients (Virginia).

Figure S3 shows that the methodology used in this study and the simpler methodologies used in other studies to estimate how much urine diversion reduces greenhouse gas emissions from wastewater treatment are often within a reasonable range.[51,52] However, the benefits from increasing urine are not linear due to elimination of chemical requirements or changes in wastewater treatment plant configuration, so the use of a linear offset results in some level of inaccuracy. For example, one offset methodology (Kavvada et al. 2017, including substrate emissions) estimated reductions in greenhouse gas emissions from wastewater treatment within 1% of the 5-stage Bardenpho treatment plant modeled in this study at 60% of urine diverted. At other levels of diversion it underestimated and overestimated these reductions by 20% and 53% respectively.

Sensitivity Analysis

Figures S4-S7 demonstrate that the results of this study were largely robust. Urine diversion always decreased freshwater use and EP. The number of repetitions where urine concentration increased global warming potential and cumulative energy demand were negligible, but occurred occasionally for struvite and ammonium sulfate when renewable electricity was used. Urine concentration alternatives did increase acidification potential in a few repetitions with the Five-Stage Bardenpho when renewable electricity was used, and approximately 30% of repetitions in the single aeration basin. The acidification potential for struvite and ammonium sulfate was always higher than the conventional alternative even as the efficiency of ammonium sulfate use approached 100%. Figures 4and S8 show that urine concentration typically had a better environmental performance than struvite and ammonium sulfate. These differences were more pronounced when producing electricity had lower environmental impacts because the added burden of electricity consumption to concentrate urine was lessened. Environmental improvements in global warming potential, cumulative energy demand, and acidification potential categories are highest in locations with electricity produced from fossil fuels and large levels of nutrient removal, as shown in Figures S4-S7. Environmental improvements are also greater in locations with less wastewater volume per person and lower performing aeration systems.

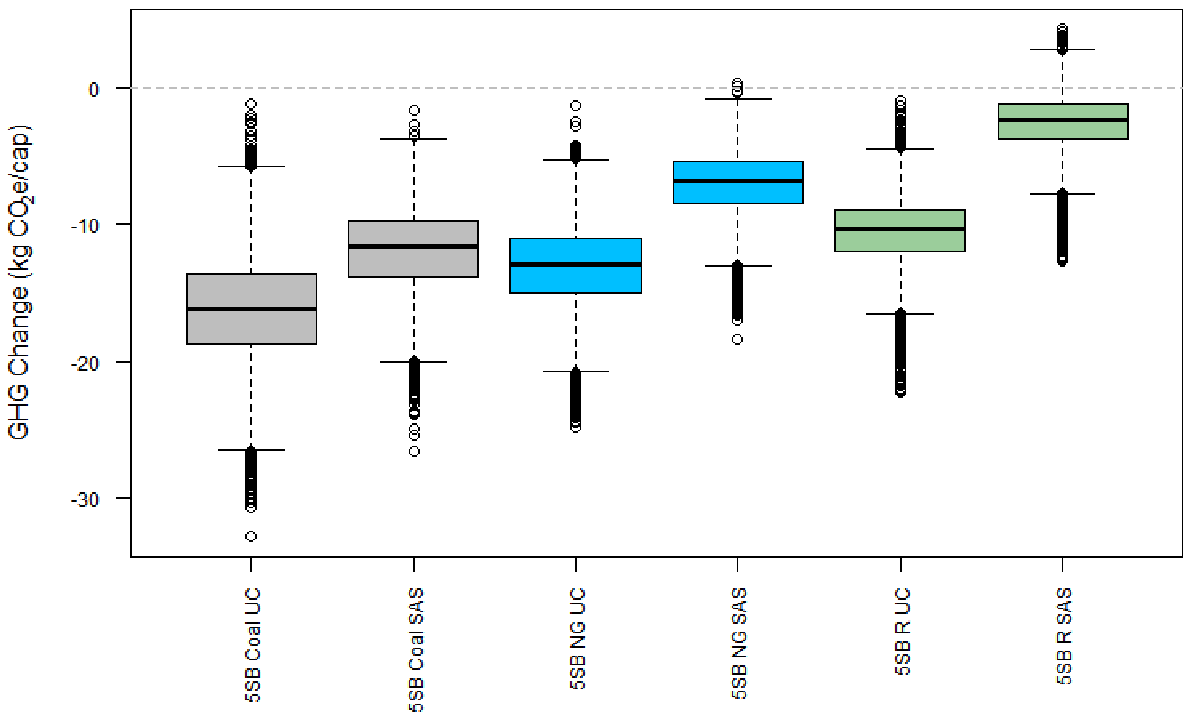


Figure 4. Box plot comparing greenhouse gas emission changes of urine concentration alternatives compared to struvite and ammonium sulfate alternatives. All data shown are from the 5-Stage Bardenpho plant modeled. UC is short for Urine Concentration, and SAS is short for Struvite and Ammonium Sulfate. Gray plots indicate coal is used, blue indicate natural gas, and green indicate renewable electricity. Everything below the dashed gray line indicates a reduction in greenhouse gas emissions.

Tables S17 and S18 show that excluding fertilizer offsets from the scope can change the conclusion of the analysis. As the environmental impact of producing electricity decreased, reducing greenhouse gas emissions without considering fertilizer offsets are less likely. The exception is for urine concentration alternatives with limited nutrient removal because net electricity consumption in a municipality increases. When excluding fertilizer offsets, urine concentration alternatives often still led to reductions in greenhouse gas emissions.

DISCUSSION

Similar to other life cycle assessments,[51,52,54,55,57,58] this study found urine diversion reduced most environmental impacts. It expanded upon previous research by conducting a more comprehensive characterization of wastewater treatment and by evaluating a range of large-scale systems. Simpler methods to estimate the changes in environmental impacts of treating wastewater are valid as an approximation, but the more complete methods used in this study may be more appropriate when increased accuracy is needed or when different extents of urine diversion are being evaluated. Scenario and sensitivity analyses showed that freshwater use and eutrophication potential impacts were always reduced, global warming potential and cumulative energy demand were consistently reduced, and urine concentration usually reduced the acidification potential.

Urine collection is the uncertain aspect of this analysis due to a lack of large-scale examples. This study modeled a centralized system conveying urine from an urban area to a central processing facility in order to create a reasonable estimate of the environmental burdens from urine collection. It suggested the importance of the acetic acid dosage used for stabilization. Other options include a more distributed system consisting of multiple processing facilities strategically located throughout an urban area to reduce both the distance collected urine would need to be transported, as well as the transport time which could reduce urine stabilization requirements.[52,56,58] The optimal scale of decentralization of urine collection still needs to be assessed, and depends on many factors including topography, size, and population density.[50] Large-scale urine collection is at an early stage of development, and may differ significantly from the urine collection system in this study, which was selected as a reasonable case.

The advantages urine diversion provides wastewater treatment are clearly demonstrated in this study and corroborated by previous research.[18,55,59] Where nutrient removal is practiced, these primarily include elimination of chemical inputs (metal salts for phosphorus removal, supplemental carbon such as methanol for nitrogen removal) and reduced energy use. In many cases urine diversion can eliminate the need to expand existing wastewater treatment plants for nutrient removal capabilities. While not considered in this study, eliminating the need for nutrient removal could allow further changes to treatment process such as increased capture and utilization of organic matter contained in the influent wastewater. In locations where nutrient removal is not a goal for wastewater treatment, eutrophication can be reduced as less nutrients are discharged to local waterways. Urine diversion leads to decreases in environmental impacts through a wide range of conditions, but can be a particularly effective decarbonization strategy in areas with high levels of nutrient removal, electricity produced primarily from fossil fuels, and relatively little wastewater per capita.

Producing fertilizer from urine instead of mineral sources leads to significant environmental benefits. These urine-derived fertilizer production methods were characterized using laboratory and demonstration scale-studies, [25,26,37–39,61,112] but demonstration of other available approaches[15,33,40,41,105] and larger scale systems will provide an improved basis for assessing environmental impacts.[15,33,40,41,105] They were selected to represent a range of fertilizer products and production methods. Urine concentration is more heavily dependent on energy, produces a fertilizer with nitrogen in the form of urea, retains much of the potassium in urine, and has a relatively consistent nitrogen-to-phosphorus ratio (depending on the composition of urine and whether additional nutrients are added). Struvite precipitation and ammonium sulfate largely use chemical inputs and could easily be applied with different nitrogen-to-phosphorus ratios. Throughout all electricity grids, the environmental burdens of producing concentrated urine were usually lower even as the efficiency of sulfuric acid use approached 100%. The environmental burdens of producing these urine derived fertilizers were lower than synthetic fertilizers, and will be significantly improved as use of sulfuric acid for ion exchange and energy for reverse osmosis are optimized, or renewable energy is used for urine concentration.

The urine-derived fertilizers evaluated could be applied similarly to fertilizers commonly used in the US.[113] Beyond the impacts of fertilizer production, other important factors such as the higher popularity of single-nutrient fertilizers will affect which fertilizers are produced.[113] Implementation efforts need to consider the fertilizer demands of adjacent communities and the transportation costs and environmental impacts associated with shipping urine-derived fertilizers from population centers.[12,114]

Urine can replace a significant fraction of synthetic fertilizers. Researchers estimate 16-30 kilograms of nitrogen and 4 kg of phosphorus in fertilizer are currently used per person per year in affluent countries.[115–118] If all nutrients were recovered from domestic wastewater it would likely produce less than 5 kg of nitrogen and 1 kg of phosphorus per person. Regardless, urine diversion can provide significant environmental benefits and can be used with other strategies such as dietary changes, manure application, and reduction of nutrient runoff during mineral extraction and fertilizer application to significantly improve nutrient use efficiency.[115,116]

The development of large-scale urine collection and processing systems is still at a conceptual stage. Research is ongoing to understand and address the many challenges of urine diversion, including economic, market and regulatory acceptance,[12,26,43,51,52,58,119–121] potential user error,[26,122] risk aversion and lack of confidence in performance,[8,43,120] and lock-in to conventional systems.[120,123] Irrespective of the urine processing method considered, net benefits were observed for each scenario evaluated. In some cases the environmental benefits associated with water and wastewater management alone were sufficient to offset the environmental burden associated with urine collection, processing, and transport. The analyses presented here clearly indicate that the more well-defined benefits (reduced wastewater management requirements and avoided synthetic fertilizer production) exceed the environmental impacts of urine collection, processing, and transport, suggesting that further efforts to develop such systems are warranted.

Supporting Information: Further descriptions of the scope, further details of the inputs and sensitivity analysis, and supplemental results are supplied as Supporting Information

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