Countering the Porcelain Dream: Key Findings from an Evaluation of the Global Nitrogen Cycle, a Fundamental Characterization of Fresh Faeces, and a Campus Composting Toilet

by

Claire M. Remington
B.A., Reed College, Portland, OR, USA, 2011

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We acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

When we consider global sanitation from within the framework of sustainable development, we are both failing to meet the needs of the present and are jeopardizing the capacity of future generations to do so. The primary function of sanitation and waste treatment is the protection of public health, but it is urgent that we also consider the long-term sustainability of sanitation and waste treatment systems. Our choice of sanitation and waste treatment systems is intimately connected to the greatest equity and sustainability challenges of our time, and we need something better than the Porcelain Dream (i.e. flush toilets, sewerage, and centralized conventional wastewater treatment). This thesis explores the design of sustainable sanitation systems from three different but complementary perspectives:

1. In a material flow analysis (MFA), I evaluate the positive impact of ecological sanitation (or the reuse of nutrients in excreta for agriculture) as an intervention to mitigate nitrogen pollution and improve stewardship of the global nitrogen cycle. I find that ecological sanitation can substitute 51% of nitrogenous fertilizer use, reduce discharge of nitrogen to waterways by 71%, decrease nitrous oxide (N_2O) emissions by 34%, and improve the circularity of the agricultural-sanitation nitrogen cycle by 22%.
2. Through environmental engineering research, I derive fundamental drying characteristics of fresh faeces to support the development of ecological and sustainable sanitation. Based on this characterization, I propose the use of the Guggenheim, Anderson, and de Boer (GAB) model for predicting the relationship between water activity (a_w) and equilibrium moisture content, calculating the heat of sorption, and estimating the corresponding energy requirements for drying of fresh faeces. Given an anticipated range of initial moisture contents of 63 to 86%, I estimate an energy requirement of 0.05 to 0.4 kJ/mol to inactivate pathogens in fresh faeces.
3. Via an evaluation of the composting toilet project at the University of Victoria (UVic), I explore factors critical to promoting a paradigm shift from the conventional to more ecological and sustainable systems. I identify the following as factors that facilitated implementation in the Exploration and Adoption/Preparation phases: supportive and self-reinforcing research and outcomes, favorable adopter characteristics, and the technology's beneficial features.

The overall objective of the research is to communicate that the design of sustainable sanitation systems is urgent, with implications both locally and globally, and to provide information to support a shift towards more sustainable sanitation systems.

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Abbreviations

$\%H_2O$	Wet basis % moisture content of the wet sample
A (B, C, K, etc.)	Constants used in the MSI models
ASTTBC	The Applied Science Technologists and Technicians of BC
a_w	Water activity
BC	British Columbia
BCCI	British Columbia Coalition Institute
BET	Brunauer-Emmett-Teller model
CCG	The Campus Community Garden at UVic
COD	Chemical oxygen demand
EPIS	Exploration, Preparation/Adoption, Implementation, Sustainment
Facilities Management	The Department of Facilities Management at UVic
GAB	Guggenheim, Anderson, and de Boer model
LMICs	Low and middle income countries
MAPE	Mean absolute percentage error
m_f	Final weight of sample at equilibrium
MFA	Material flow analysis
m_i	Initial weight of same sample
MSI	Moisture sorption isotherm
Mt N	Metric tons of nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4	Ammonium
NO_3	Nitrate
NO_x	Nitrogen oxide
NUE	Nitrogen Useful Efficiency
OCPS	The Office of Campus Planning and Sustainability at UVic
PH2E	Public Health & Environmental Engineering Lab
RMSE	Root mean squared error
ROWP	Registered Onsite Wastewater Practitioner
RSE	Residual standard error
SDG	United Nations Sustainable Development Goal
SOIL	Sustainable Organic Integrated Livelihoods
SSD	Source separation and decentralization
T	Temperature
The Manual	The Manual of Composting Toilets and Greywater Practice
UVic	University of Victoria
WaSH	Water, Sanitation, and Hygiene
x	Equilibrium moisture content (g water/g dry)
X_m	Monolayer water content

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"Let me keep my mind on what matters, which is my work, which is mostly standing still and learning to be astonished," (Mary Oliver).

1. Introduction

I am a master's student in the Public Health & Environmental Engineering (PH2E) Lab in the Civil Engineering Department at UVic. Previously, I was working for the organization SOIL (Sustainable Organic Integrated Livelihoods) in Haiti that provides a household sanitation service in Cap Haitien, Haiti. My research with the PH2E Lab explores the design of sustainable sanitation systems from three different but complementary perspectives: lab-based environmental engineering work to characterize fresh faeces, big-picture desk-based research looking at the flow of nitrogen through global agriculture and sanitation systems, and the installation of a composting toilet on the UVic campus. My research objective is to communicate that we are experiencing a global sanitation crisis from the joint perspective of equity and sustainability.

The goal of sustainable development is to meet the needs of the present without compromising the ability of future generations to do so [1]. When we consider global sanitation from within the framework of sustainable development, we are both failing to meet the needs of the present and are jeopardizing the capacity of future generations to do so. Sasha Kramer, Co-founder and Executive Director of SOIL, started her work in Haiti as a human rights advocate where she recognized that poverty, and access to fundamental services like water and sanitation, are pervasive human rights abuses. I learned from her that safe, secure, and dignified sanitation is a fundamental human right (and it was recognized as such by the United Nations General Assembly in 2010 [2]):

> "The manner in which a person is able to manage bodily functions of urination, defecation, and menstruation is at the core of human dignity [3]."

Despite this recognition and the work done by SOIL and countless other stakeholders, an estimated 61% of the global population, or 4.6 billion people, is without access to household-level sanitation and waste treatment where excreta is contained and treated [4], [5]. About 88% of all diarrheal deaths are attributed to inadequate water, sanitation, and hygiene (WaSH) systems and diarrheal disease caused over 71 million disability-adjusted life years (i.e. estimated loss of healthy life years) in 2010 [6], [7]. Lack of access to basic services and infrastructure, like sanitation, is associated with endemic poverty: poor sanitation increases the probability of health shocks, and poorer households (and particularly those in contexts without a social safety net) are less economically resilient such that health shocks are likely to keep households in or drive them towards poverty conditions [8]. The inequity is one of economics, public health, poverty, and morality.

In addition to the inequity that exists between those that do and do not have access to safe, secure, and dignified sanitation systems, there is a secondary inequity that exists between those that are using unsustainable sanitation systems and future generations. Safely managed sanitation systems are defined as those household-level sanitation systems that ensure that excreta are both safely contained and treated [4]. Safely managed sanitation systems are effective in minimizing contact between the public and the pathogens found in excreta. However, sanitation systems that are effective in protecting public health may still disrupt planetary boundaries and are thereby an unsustainable sanitation system. Rockstrom et al.'s seminal work on planetary boundaries proposes that there are nine key global subsystems that circumscribe a "safe operating space" for humanity; if we exceed the limits of key thresholds for these subsystems, we threaten irreversible environmental change [9]. For example, conventional sewerage and wastewater treatment systems are effective in protecting public health but can discharge nutrients, micropollutants, consume freshwater, and emit greenhouse gas emissions thereby disrupting at least five of Rockstrom’s subsystems and the overall resilience of the planet and its capacity to provide for future generations.

This is what I refer to as the “Porcelain Dream:” flush toilets, sewerage, and centralized wastewater treatment are both miraculous and imperfect. The primary objective of sanitation is the protection of public health, but it is urgent that we consider the long-term sustainability of sanitation and waste treatment systems from the perspective of its impact on planetary system functioning. Our choice of sanitation and waste treatment systems is intimately connected to the greatest equity and sustainability challenges of our time, and we need something better than the Porcelain Dream.

In Chapter 2, “The potential impact of ecological sanitation on the nitrogen cycle,” I present a material flow analysis (MFA) where we evaluate the positive impact of ecological sanitation (or the reuse of nutrients in excreta for agriculture) as an intervention to mitigate nitrogen pollution and improve stewardship of the global nitrogen cycle. The MFA shows a need to improve the sustainability of our sanitation and waste treatment systems on a global scale. Conventional wastewater and centralized treatment (i.e. the Porcelain Dream) negatively impacts the global nitrogen cycle. An alternative to conventional wastewater and centralized treatment is ecological sanitation. The results of “The Potential Impact of Ecological Sanitation on the Nitrogen Cycle” quantifies how ecological sanitation has the potential to reduce sanitation and waste treatment’s impact on the nitrogen cycle by reusing the nitrogen in excreta for agricultural purposes. In other words, we can improve our stewardship of a biogeochemical cycle through an improved infrastructure choice.

However, a paradigmatic shift in what is considered default or conventional will require (among other factors) the development of new technology. Drying, or dewatering, has been identified as a potential treatment mechanism that could be integrated to the provision and development of ecological and sustainable sanitation technologies and services. The objective of the work done in Chapter 3, “Measurement and modelling of moisture sorption isotherm and heat of sorption of fresh faeces,” is to derive fundamental characteristics of faeces to inform process and technology design thereby supporting a larger shift towards more sustainable sanitation and waste treatment infrastructure choices. This research is the first step in developing improved drying processes and technologies for sanitation and waste treatment.

Technological advances can be used to mitigate human systems’ negative impact on the planet. The principal result of Chapter 3 is a scalar value that can be used in the development of technology and processes that manage and treat human excreta via drying or dewatering as part of sustainable sanitation and waste treatment technologies and processes. New technology and processes are important and as essential is understanding how to facilitate systematic uptake of those sustainable technologies and processes. In Chapter 4, “The Exploration and Adoption/Preparation of a composting toilet system for the University of Victoria,” we evaluated what factors facilitate or impede the implementation of a sustainable sanitation technology.

This is a manuscript-style thesis i.e. each chapter is written as a stand-alone document that will be (or already has been) submitted for publication. The variations in structure, composition, methodology, and language are reflective of the journal requirements. Each manuscript has several contributors, but the work here is primarily mine with regards to intellectual conceptualization, methodology, data analysis, and preparing the original drafts. In addition to manuscripts in preparation for publication, the research was presented via poster and oral presentations (Table 1-1). I wrote each manuscript in the “anonymized, pseudo-objective, author-evacuated prose of mainstream academic work” [10], but I intended to write the

Introduction, Discussion, and Reflections in such a way that reflects how emotionally present and implicated I am in this work. We live in a precarious time, and it is critical to give space to grieve – and then cultivate an optimistic path forward. I resonate with the words of Mary Oliver: "*Pay attention, be astonished, and tell about it*." It is a daily exercise in joy and a command to pay attention to our environment in such a way that moves beyond the limitations of science to a common vision and a shared sense of humanity.

Ultimately, this thesis evaluated how to better provide fundamental and universal access to a basic human right: dignified sanitation that safely contains and treats excreta, in the present and in the future, and for all.

Table 1-1 Manuscripts and presentations produced from the contents of the master's research

Thesis Chapter	**Manuscript or Presentation**
Chapter 2	**Remington, C.**, Kennedy, C., Whittredge, P., & Dorea, C. (2019). "The potential impact of ecological sanitation on the nitrogen Cycle," (*in preparation for submission to Nature Sustainability)*.
	Remington, C., Kennedy, C., Whittredge, P., & Dorea, C. (2019). "Improving the circularity of nitrogen use in the global agriculture-sanitation system," (*submitted for oral presentation at Dresden Nexus Conference 2020: Circular Economy in a Sustainable Society)*.
Chapter 3	**Remington, C.**, Bourgault, C., & Dorea, C. (2019). "Measurement and modelling of moisture sorption isotherm and heat of sorption of fresh faeces," *(submitted to Environmental Science: Water Research & Technology)*.
	Remington, C., Dorea, C., & Bourgault, C. (2018). "Characterizing fresh faeces drying for application to a humanitarian emergency toilet design." Accepted for oral presentation at WEST 2018 Conference, Vancouver, BC, Canada.
	Remington, C., Bourgault, C., & Dorea, C. (2018). "Improving understanding of faecal drying for application to a humanitarian emergency toilet design." Accepted for poster presentation at WEDC Conference 2018, Nakuru, Kenya.
	Remington, C., Bourgault, C., & Dorea, C. (2019). "Moisture sorption characteristics of fresh faeces." Accepted for oral presentation at WEST 2019 Conference, Vancouver, BC, Canada.
	Remington, C., Bourgault, C., & Dorea, C. (2019). "The distribution of water in fresh faeces can be modeled to predict the energy requirements for drying (and thus pathogen inactivation)." Accepted for poster presentation at UNC Water and Health Conference 2019, Chapel Hill, North Carolina.
Chapter 4	**Remington, C.** & Dorea, C. (2019). "The Exploration and Adoption/Preparation of a composting toilet system for the University of Victoria," (*in preparation for submission to Blue-Green Systems*).
	Remington, C. (2019). Implementing composting toilet systems in BC and worldwide. Accepted for oral presentation at BCWWA 2019, Victoria, BC, Canada.

2. The potential impact of ecological sanitation on the nitrogen cycle

2.1. Abstract

The global agricultural-sanitation nitrogen cycle is linear. The negative consequences of this linearity are a continued dependence on carbon-intensive linear inputs (nitrogenous fertilizer produced through the Haber-Bosch process), discharge of reactive nitrogen to waterways with significant impacts on biodiversity, and denitrification/volatilization of reactive nitrogen to the atmosphere as greenhouse gasses and smog precursors. To estimate nitrogen loss to the environment, global nitrogen flows were modeled in material flow analyses and Sankey diagrams. Here we show how widespread implementation of ecological sanitation—defined as the reuse of nutrients in excreta for agriculture—has the potential to substitute 51% of nitrogenous fertilizer use, reduce discharge of nitrogen to waterways by 71%, decrease nitrous oxide (N_2O) emissions by 34%, and improve the circularity of the agricultural-sanitation nitrogen cycle by 22%. The direct benefits include a decreased dependence on linear inputs to global agriculture and mitigated nitrogen pollution.

2.2. Introduction

Our present human global agricultural and sanitation systems, comprised of processes from food production to excreta management, are linear with respect to freshwater and nutrient cycles. A prime example is the production of nitrogen-based fertilizer from atmosphere nitrogen N_2 via the Haber-Bosch process [11], which drives N away from N_2 and ultimately toward NH_3 and NO_X atmospheric emissions at a rate far beyond non-industrial equilibrium. Production of nitrogen-based fertilizer via Haber-Bosch has dramatically increased food supply and reduced hunger worldwide, however only about 50% of nitrogen-based fertilizer applied to crops is assimilated by plants—the remainder is released to the environment with deleterious impacts [12], [13].

Every stage of the agricultural-sanitation system is associated with emissions of N_2O, ammonia (NH_3), and nitrogen oxide (NO_X) to the atmosphere [14]. N_2O is a greenhouse gas with a global warming potential more than 310 times greater than carbon dioxide [15]. Atmospheric NH_3 and NO_x are air pollutants that can migrate to soil and water surfaces, resulting in soil acidification and eutrophication, or react to form aerosol particles associated with poor air quality, human health impacts, and global climate change [16], [17]. Reactive nitrogen (in the form of nitrate (NO_3) and NH_3 species) is also released into water bodies directly from agriculture or as human excreta. Reactive nitrogen in water contributes to surface water acidification, eutrophication of surface waters, loss of biodiversity, and decline in marine ecosystem resilience [14], [18], [19]. The resulting disturbances to the global nitrogen cycle have been and will continue to be comprehensive.

Not only is the global agricultural and sanitation system unsustainable from a resource management perspective, it is also socio-economically inequitable. The global increase in fertilizer use–and the resulting agricultural production and related socioeconomic development–has been unequally distributed throughout the global population [20]. Low and middle income countries (LMICs) are typically characterized by lower rates of nitrogenous fertilizer application, with an input to crop production of 0 to 15 kg nitrogen per capita per year, compared with higher rates of nitrogenous fertilizer application in high income countries, from 15 to greater than 60 kg nitrogen per capita per year [18]. Additionally, 55% of the global population lacks access to safely managed sanitation services, which is defined as access to a sanitation facility at the household where excreta is safely treated [21]. Without safely managed sanitation services, excreta either immediately enters the environment as in the case of open defecation, or is temporarily postponed from entering the environment, either via inadequate collection, transport, or treatment systems. These systems not only fail to manage the nitrogen discharge to the environment, they also do not provide adequate protection of public health. Thus to achieve a comprehensively successful human health outcome the imperative to improve food security in LMICs must be coupled with the need to implement sanitation and waste treatment with resource recovery services that manage the reactive nitrogen content of human excreta [22]–[24].

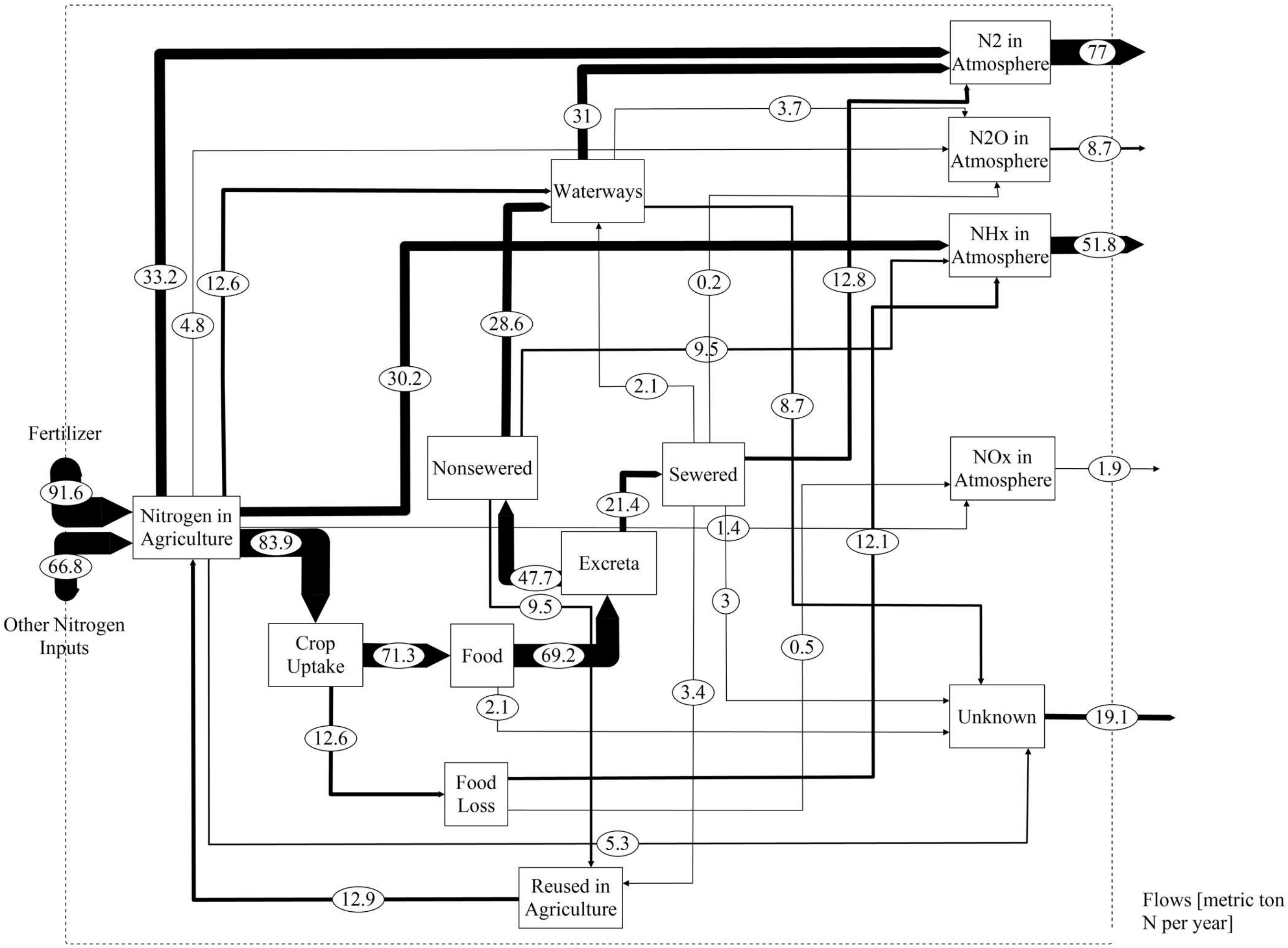
There has been considerable interest and investment in the development of sanitation technologies that can recover nutrients and energy from wastewater and excreta [25]. Ecological sanitation is an approach for sustainably managing the fluxes of water and nutrients common to both sanitation and agriculture, especially nitrogen [26], [27]. The term has been used to describe waste treatment methods that recover water and nutrients from excreta for use in agriculture as well as a general philosophy of recognizing excreta as a resource rather than waste [28]. Ecological sanitation is broadly defined as the reuse of resources and nutrients from excreta in agriculture, and as such does not refer to any one specific technology [29].

Here we assess the potential for ecological sanitation to improve the circularity of the agricultural-sanitation nitrogen cycle, thereby mitigating nitrogen pollution. We catalogue the mass balance of nitrogen in the combined agricultural-sanitation system for 2010 and compare to new relationships for nitrogen use efficiency and nitrogen content of excreta (see Methods and Supplementary Information). Recovering nutrients from excreta could improve the management of nitrogen—with implications for improving global food security and access to safe sanitation—and could stabilize the negative impacts to the global nitrogen cycle. In this work we examine these impacts under two scenarios of higher use of ecological sanitation systems.

2.3. Results and Discussion

2.3.1. Nitrogen loss in the global agriculture and sanitation system

The estimated loss of nitrogen (the ratio of linear outputs to inputs to the system) to the environment from human systems is 92% (Figure 2-1; see Methods and SI). Nitrogen is lost to the environment from the global agricultural and sanitation system through discharges to the environment and atmosphere; these discharges impede the recirculation of nitrogen to the agricultural system. Most of this loss occurs within agriculture: only 58% of the nitrogen inputted to agriculture is transformed into food.



Global Agricultural and Nitrogen System

Figure 2-1 Flow of nitrogen in the global agricultural and sanitation system (metric tons of nitrogen (Mt N)) produced with stan2web [30]. The estimated loss of nitrogen (the ratio of linear outputs to inputs to the system) to the environment from human systems is 92%. This is calculated as the ratio of the linear outputs (exiting the system boundary on the right of the diagram) to the linear inputs (entering the system boundary on the left of the diagram).

In 2010, more than half of the total nitrogen used in agriculture was sourced from synthetic nitrogenous fertilizer [31]. The uptake of nitrogen by crops is correlated with the total nitrogen used in agriculture (t-stat = 10.582; P value = 0.1609; adjusted $R^2 = 0.8162$, calculated from [31]) (Figure 2-2). Improving the relationship between the total nitrogen used in agriculture and crop uptake of nitrogen (i.e. the Nitrogen Useful Efficiency (NUE)) has been identified as a key nitrogen pollution mitigation strategy [13]. The total nitrogen used in agriculture is defined as the sum of nitrogen in synthetic fertilizer, nitrogen deposition, nitrogen fixation, and manure. Crop uptake of nitrogen has been calculated by considering the nutrient content of various crop groups and the geospatial distribution of those crop groups [31].

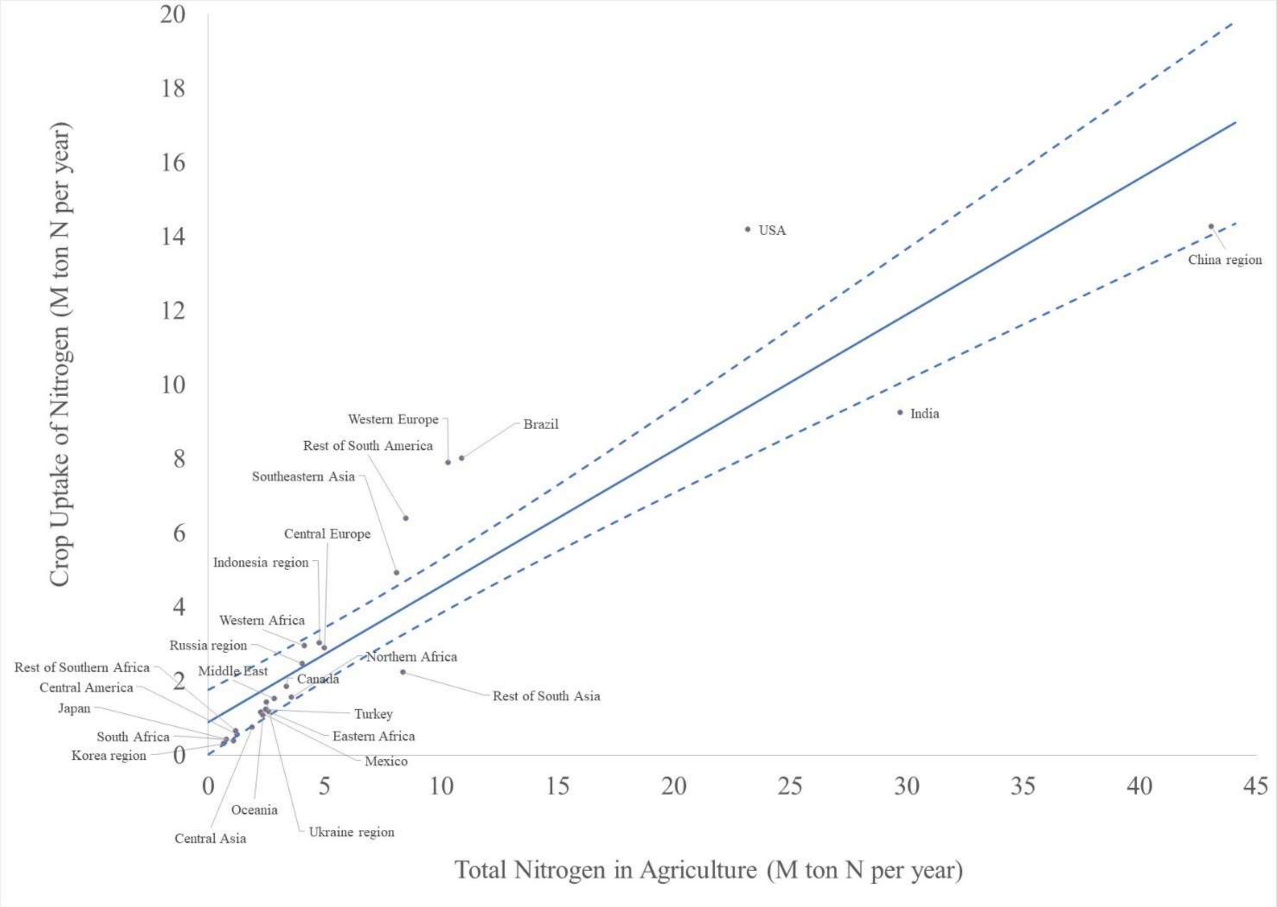


Figure 2-2 Relationship between the total nitrogen used in agriculture and crop uptake of nitrogen (i.e. the NUE). Crop uptake of nitrogen was calculated by Bouwman et al. by considering the nutrient content of various crop groups and the geospatial distribution of those crop groups [6]. The dashed lines indicate the 95% confidence interval for the trendline.

The nitrogen inputs to agriculture are used to produce food that contains protein, a form of nitrogen that is digestible by humans and then ultimately excreted [32]. The estimated excretion of nitrogen per capita varies primarily by variation in dietary intake [25], [33], [34]. Given data for five countries, the nitrogen content of excreta per capita is correlated with the total nitrogen applied in agriculture per capita (t-stat = 2.479; P value = 0.0894; adjusted $R^2 = 0.5626$), as can be seen in Figure 2-3.

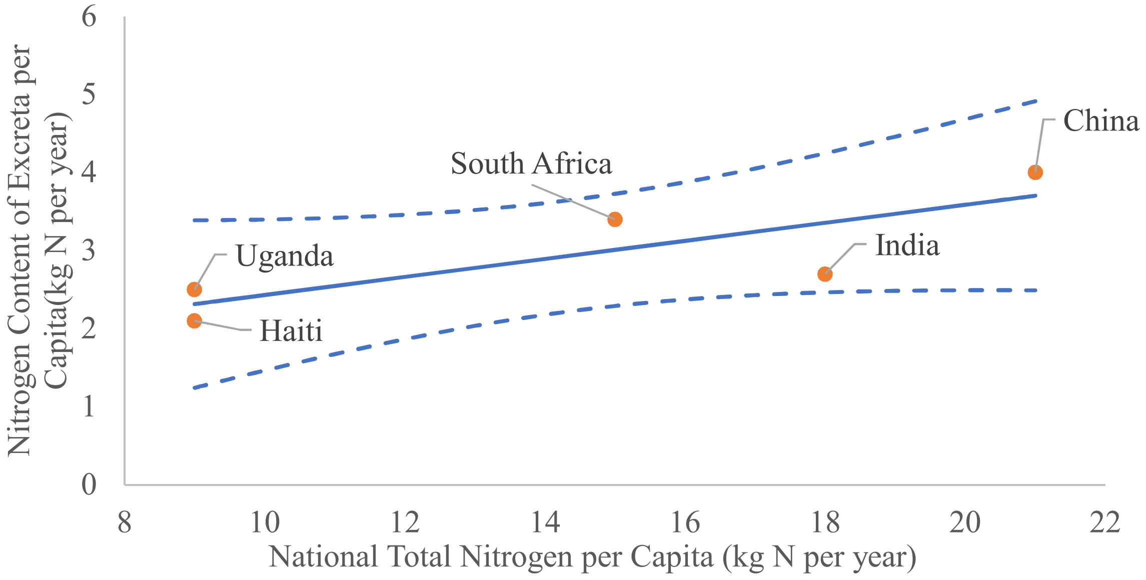


Figure 2-3 Comparison of nitrogen content of excreta per capita with total nitrogen used in agriculture. The dashed lines indicate the 95% confidence interval for the trendline.

Based on the relationship in Figure 2-3 and assuming there is no export or import of nitrogen (as food), the estimated loss of nitrogen between inputs to agriculture and excreta is 88%. In comparison, this value calculated from Figure 2-1 is 60%. Given that the regression analysis in Figure 2-3 was performed with data from LMICs and the analysis in Figure 2-1 is a global analysis, it is likely that the difference can be attributed to the import of nitrogen (as food). In other words, the 28% difference potentially represents nitrogen that is imported as food by the five countries shown from the rest of the world.

In 2017, only 45% of the global population had access to safely managed sanitation [21]. About 69% of this 45% (i.e. 31% of the global population) relied on sewer-based sanitation facilities [21]. Nitrogen loss from sewered sanitation varies depending on the extent of treatment at the connected wastewater facility: some facilities can achieve up to 80% nitrogen removal from incoming wastewater before discharge as effluent [35]. The fate of nitrogen removed from incoming wastewater is denitrification to N_2 and N_2O, or mineralization in sludge [36]. The end-uses of sludge include landfill disposal, combustion for energy production, and reuse in agriculture [37]. About 50% of sludge is reused in agriculture [38]–[41].

In comparison, it is estimated that nonsewered sanitation systems – which includes both those systems that do treat the excreta as well as those that do not – discharge 60% of nitrogen to waterways. The nitrogen that is recovered from nonsewered sanitation systems for agricultural use is typically untreated—this material poses public health risks but potentially benefits agricultural productivity.

Under the current sanitation system paradigm (Figure 2-1), only 9.5% of the nitrogen in nonsewered excreta is reused in agriculture. Hypothetically, if 100% of all the nitrogen mineralized in wastewater treatment plant sludge were reused in agriculture, then 23% of nitrogen in excreta would be reused (given the current ratio of sewered to nonsewered sanitation systems worldwide). In general, conventional wastewater systems are suboptimal for the recovery of nutrients because of the high dilution rate of the systems [39]. Additionally, conventional wastewater systems are designed for the removal of nutrients prior to discharge instead of nutrient recovery; it is only “advanced” wastewater treatment plants that consider nutrient recovery (and other secondary objectives, like the treatment of micropollutants), which entail a higher capital cost and larger footprint [42], [43]. Primary treatment consists of the removal of settleable organic and inorganic solids by sedimentation; secondary treatment typically involves the removal aerobic biological treatment to remove biodegradable dissolved organic matter; and tertiary treatment (i.e. advanced treatment) refers to the specific removal of wastewater constituents that cannot be removed by secondary treatment [44]. Additional sustainability challenges of conventional wastewater systems include energy use, nutrient losses, sequestration of toxic chemicals and heavy metals in biosolids, and greenhouse gas emissions [43].

2.3.2. Nitrogen recovery of ecological sanitation

The goal of ecological sanitation systems is to enable higher potential recovery of nitrogen in excreta. The maximum nitrogen recovery attained thus far from excreta by ecological sanitation is 86% via thermophilic composting in a household latrine [45]. This represents an increased nitrogen recovery of 63% to 72% compared with the current combination of sewered and nonsewered sanitation systems. Additionally, thermophilic composting has been used to meet the World Health Organization standard for pathogen inactivation in excreta: maintaining a temperature of 50˚C for 7 days [46]. Thus, widespread implementation of ecological sanitation can improve nitrogen recovery, mitigate pollution and climate change impacts associated with nitrogen loss to the environment, and reduce the negative public health impacts associated with 55% of the global population lacking access to sanitation systems that safely treat excreta prior to discharge to the environment. Ecological sanitation strategies like themophilic composting have the potential to improve nitrogen recovery in safely managed sanitation systems, both sewered and nonsewered, and mitigate the spread of pathogens associated with unsafely managed sanitation systems.

Regarding other public health impacts associated with the reuse of excreta in agriculture, the fate of emerging contaminants like pharmaceuticals, personal care products, and microplastics in human excreta is a relatively new field of study. In addition to emerging contaminants, sludge from wastewater treatment plants will likely include pollutants and heavy metals from industry and stormwater [42], [47], [48]. A recent study suggests that composting may degrade emerging contaminants in excreta, however this result conservatively assumes that the release of emerging contaminants and other pollutants to the environment via land application in agriculture is either equivalent to or less than what is released by sewered and nonsewered sanitation systems [49].

2.3.3. Impact of ecological sanitation on the circularity of the global agricultural-sanitation nitrogen cycle

The circularity of the global agricultural-sanitation nitrogen cycle can be defined as the ratio of circular outputs to total nitrogen demand. Estimates regarding the potential of excreta-based fertilizer to replace synthetic fertilizer vary: it has been suggested that the production of fertilizer from urine could satisfy nearly a fifth of current global nitrogen demand [40]; offset 4-12% of global synthetic fertilizer use [7]; and 29% of the synthetic fertilizer used in Hamburg could be substituted by nutrients recovered from wastewater [26]. Here we estimate that ecological sanitation (i.e. the recovery of nutrients from excreta for agricultural purposes) can recover 59 M ton N per year. This would significantly improve nitrogen cycle circularity from the current 8% to 35%. The recovered nitrogen could substitute 51% of the synthetic nitrogenous fertilizer used in agriculture (Figure 2-4A and 2-4B).

Figure 2-4A

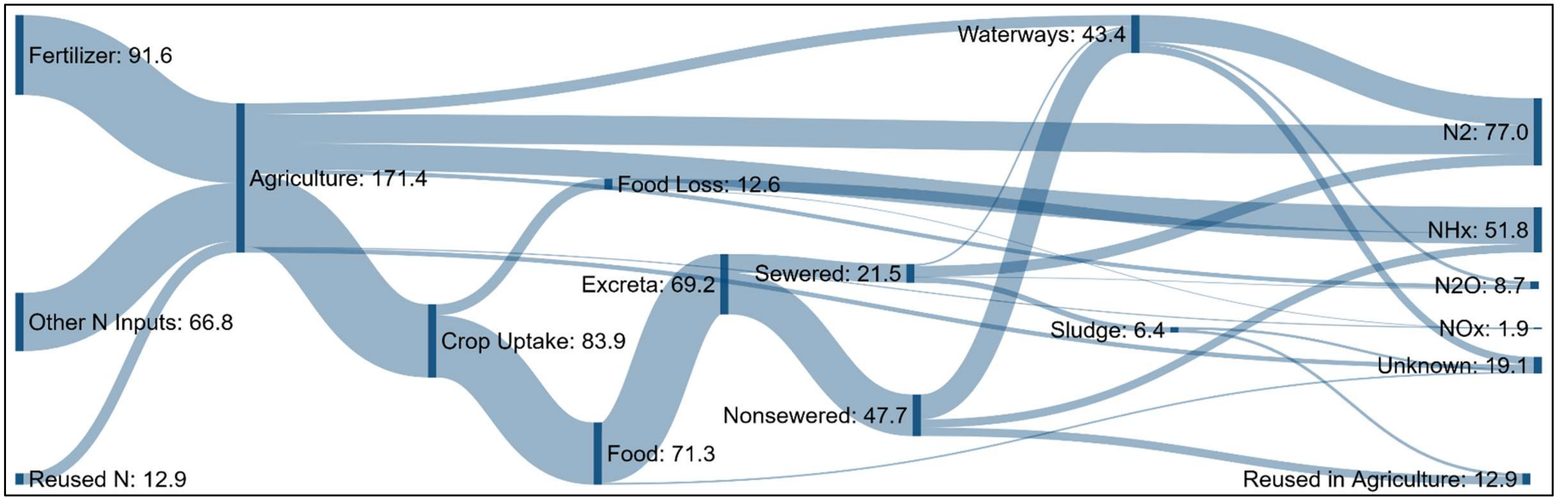


Figure 2-4B

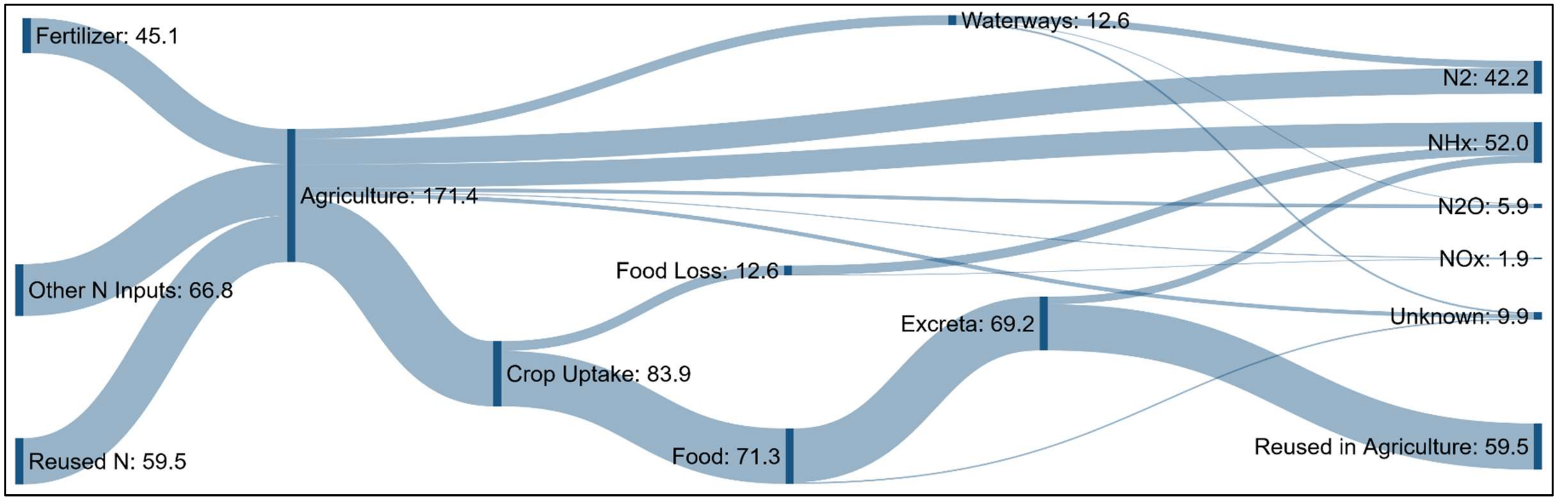


Figure 2-4 A. Flow of nitrogen in the global agricultural-sanitation system (Mt N). Figure 2-4B Flow of nitrogen in the global agricultural-sanitation system with widespread implementation of ecological sanitation to recover nitrogen from excreta for agricultural reuse .

Recirculating nitrogen in the global agricultural and sanitation system via ecological sanitation can 1) decrease linear inputs (i.e. nitrogenous fertilizer) to the system; 2) decrease linear outputs (e.g. atmospheric NO_x, N_2O, and NH_x) from the system; and 3) mitigate pollution associated with the discharge of reactive nitrogen to aquatic environments and volatilization of nitrogen to the atmosphere (Table 2-1).

Table 2-1 Summary of the impact of ecological sanitation on key components of the nitrogen balance model in M ton N per year. The first scenario is 100% of the global population is served by an ecological sanitation system with a maximum nitrogen recovery of 86% The second scenario is the provision of ecological sanitation systems to the global population without access to safely managed sanitation system (54%) such that 100% of the global population has access to safely managed sanitation services.

Component of Nitrogen Balance Model		**M ton N per Year**		
		2010	**Scenario 1: 100% EcoSan**	**Scenario 2: 54% EcoSan & 100% Safely Managed**
Linear Input	Nitrogenous Fertilizer	91.6	45.1	66.6
Linear Output	NO_x in Atmosphere	1.9	1.9	1.9
	N_2O in Atmosphere	8.7	5.9	6.7
	NH_x in Atmosphere	51.8	52.0	49.6
	Unknown	19.1	9.9	14.5
Intermediate Process	NO_3^-/NH_4^+ in Waterways	43.3	12.6	20.6

Under a scenario of 100% ecological sanitation with a maximum nitrogen recovery of 86%, the magnitude of all the fluxes associated with the polluting nitrogen species decreases, except for NH_x and NO^x in the atmosphere (Table 2-1). This is compared with a scenario where all the population without access to safely managed sanitation system starts using ecological sanitation systems (i.e. 31% of the population with sewered sanitation, 14% with nonsewered but safely managed sanitation, and the remaining 54% with ecological sanitation). However, it is likely that the "Unknown" component is a combination of NH_x and NO_x in atmosphere (discussed further in Methods) and as such, it can be assumed that the fluxes of polluting nitrogen species in the agricultural and sanitation system decrease under 100% ecological sanitation. A significant impact of the ecological sanitation intervention in the global agricultural and sanitation system is in the 52% (Scenario 2) to 71% (Scenario 1) decrease of reactive nitrogen discharge to waterways

2.4. General Discussion

This analysis was done on a global scale, but there is the potential to improve regional food security with the widespread implementation of ecological sanitation. LMICs are typically characterized by lower rates of nitrogenous fertilizer application, and insufficient reactive nitrogen is a cause of food insecurity, increased risk of malnutrition, and lower levels of socioeconomic development [18], [32], [50]. A critical challenge of sustainable development is how to improve the food security in LMICs while mitigating the overall negative impacts of reactive nitrogen released into the environment because of agricultural activity. In other words, what level of nitrogenous fertilizer application meets food production needs, and what level is excess?

This analysis identified further areas for research, principally around the potential impact of ecological sanitation on food security and nitrogen loss as well as the practical implications of serving a greater population with ecological sanitation. There are open questions around how much ecological sanitation could potentially mitigate food insecurity, whether innovation could improve recovery of nitrogen in sanitation and waste treatment systems, and if recovered nitrogen from excreta (e.g. compost) would have a greater NUE than nitrogen fertilizer. From a practical perspective and given the advantages of ecological sanitation, what are the potential cost and barriers to implementing greater nitrogen recovery from excreta at a global scale?

In addition to the potential advantages of ecological sanitation in stewarding the nitrogen cycle, ecological sanitation technology like composting toilets have the potential to better conserve water and energy use, steward other biochemical cycles (e.g. phosphorous), manage micropollutants (e.g. hormones and pharmaceutical residues) and minimize greenhouse gas emissions [43], [51]. In other words, our choice of sanitation and waste treatment is intimately connected to the greatest planetary challenges of our time. Planners and engineers must consider how systems can be designed to assure access to basic services like access to water and safely-managed sanitation while stewarding planetary health. This is a strategic concern applicable not only to those contexts where safely-managed sanitation services have not yet been established but to all contexts. Ecological sanitation is an approach to sanitation that manages the flow of freshwater and nutrients based on sustainable biogeochemical cycles, supports agricultural productivity, mitigates negative environmental impacts, and provides a foundation for global socioeconomic equity.

2.5. Methods

2.5.1. Global agriculture and sanitation nitrogen balance model

The initial flow of nitrogen through global agriculture and sanitation is given in a published database of values showing inputs to and outputs from agriculture in 2010 [31]; subsequent flows are calculated from assumptions and ratios of the initial flows (Supplementary Information 2). The published database did not consider any of the circular outputs described in the nitrogen balance model. The analysis of nitrogen flow per year is thus limited to a single year 2010. The remaining processes were quantified by producing “transfer coefficients,” or ratios that indicate the magnitude of the fluxes. These transfer coefficients were identified via literature review. When the inputs of nitrogen for a given process in the global agriculture and sanitation system is greater than the outputs, an output flux to “Unknown” is added in application of mass balance principles. The “Unknown” output was calculated as the difference between known inputs and outputs to the process. The difference could be attributed to the compilation of data and assumption from different sources or insufficient data and assumptions. It is likely that the “Unknown” output is a combination of emissions of atmospheric NH_3 and atmospheric NOx. It is possible some key flows were omitted from the analysis. The nitrogen balance model is visualized in a MFA diagram produced with stan2web [30]. The values for the initial flow of nitrogen are based on an established model developed by experts in the field and as such are highly reliable. The remaining transfer coefficients are more variable in their reliability, but are adequate for the scope of this analysis.

2.5.2. Nitrogen loss analysis: NUE and the relationship between the nitrogen applied in agriculture and the nitrogen content of excreta

The analysis of NUE on a regional basis (Figure 2-2) and the relationship between the nitrogen applied in agriculture and the nitrogen content of excreta (Figure 2-3) were performed using a linear regression analysis in RStudio [52]. NUE was analyzed on a regional basis with data from Bouwman et al. [31]. The data used for nitrogen content of excreta is from Rose et al. [34] and compared with data for total nitrogen in agriculture from Liu et al. [18]. The slope of the line of best fit in Figure 2-3 was then calculated for comparison with the ratio of nitrogen lost between agriculture and excreta in the nitrogen balance model (Figure 2-1).

2.5.3. Nitrogen recovery of ecological sanitation

The maximum nitrogen recovery of ecological sanitation was determined by 1) identifying waste treatment methods that recover nutrients, 2) performing a literature review for each treatment method regarding its nutrient recovery potential, and 3) defining the maximum nitrogen recovery of ecological sanitation as equivalent to the method identified with the highest percent nitrogen recovery. The percentage nitrogen recovery is defined as the amount of nitrogen remaining in the sanitized material compared with the initial amount of nitrogen present in the excreta. It was assumed that 100% of the global population is using a form of ecological sanitation which enables an 86% recovery of the nutrients in excreta. (A comprehensive list of waste treatment methods that recover nutrients is given in Supplementary Information 1.) The impact of ecological sanitation on the global agricultural and sanitation nitrogen balance model is analyzed using the same series of assumptions and ratios used in the initial global agriculture and sanitation nitrogen balance model and then visualised using SankeyMATIC [53].

2.6. Supplementary Information 1

The following are waste treatment methods that have been identified as nutrient-recovery methods

Table 2-2 Waste treatment methods with the potential to recovery nutrients from excreta and the potential nitrogen recovery possible with the given waste treatment method.

Treatment	Nutrient-recovery technology
Biological	Anaerobic treatment
	Aerobic treatment
	Planted drying beds
	Composting
	Lactic acid fermentation
	Algae production
	Vermicomposting
	Black-soldier fly composting
	Aquaculture
	Microbial cells
Chemical	Precipitation
	Stripping
	Acid leaching
	NH_3 treatment
	Alkaline stabilisation
Thermo	Pyrolysis
	Incineration
	Solar drying
Physio	Membranes
	Adsorption/Filtration

There is published information about percentage nitrogen recovery available for the following waste treatment methods [54].

- Planted drying beds: 35 to 70% [55]
- Composting: 86% [45]
- Black-soldier fly composting: Low; assimilation of nitrogen into the larval biomass [56]
- NH_3 treatment: Low; some evidence suggests that there is a potential for sanitisation of faecal sludge by intrinsic NH_3, but most waste treatment systems that operate by NH_3 treatment involve the addition of nitrogen [57], [58]
- Pyrolysis: 0%, nitrogen lost [54]
- Incineration: 0%, nitrogen lost [54]
- Solar drying: 81% [59]

2.7. Supplementary Information 2

The table below show the data used and assumptions made to construct the flows in Figures 2-4A and 2-4B for 2010 and a hypothetical scenario where 100% of the global population is using a form of ecological sanitation which enables an 86% recovery of the nutrients in excreta. When applicable, the logic behind assumptions and calculations is also shared.

Table 2-3 The assumptions and associated references used to construct the Sankey diagrams. The unit of the flow if M ton N per year. The text used to construct flow in SankeyMATIC [53] is constructed as “SOURCE [AMOUNT] TARGET,” for example “Fertilizer [92] Agriculture.” The first scenario is 100% of the global population is served by an ecological sanitation system with a maximum nitrogen recovery of 86% The second scenario is the provision of ecological sanitation systems to the global population without access to safely managed sanitation system (54%) such that 100% of the global population has access to safely managed sanitation services.

Flux		**Transfer Coefficient**		**2010**	**Scenario 1**	**Scenario 2**	**Notes with Reference**
From	**To**	**Value**	**Relative To**	**M ton N per year**			
Fertilizer	Agriculture			91.6	***45.1***	66.6	A database of agricultural nitrogen input and output data by the 26 world regions for 2010 was used for values of total nitrogen applied to agriculture, crop uptake of nitrogen, nitrogen from fertilizer, nitrogen runoff (to waterways), and nitrogen surplus [31]. The “Other N Inputs” (in Bouwman et al., the sum of nitrogen applied in agriculture manure, fixation, and deposition) value was adjusted by the calculated value of nitrogen reused in agriculture (sum of fluxes “from Sewered to Agriculture,” “from Nonsewered to Agriculture,” and “from Excreta to Agriculture (with max nitrogen recovery)”). In Scenarios 1 and 2, the flux from Fertilizer to Agriculture was adjusted by the increased nitrogen flux from “Reused from Sanitation” to “Agriculture.”
Other Nitrogen Inputs	Agriculture			66.8	66.8	66.8	
Agriculture	Crop Uptake	49%	Agriculture	83.9	83.9	84	
Agriculture	NO3/NH4 in Waterways	7%	Agriculture	12.6	12.6	12.6	
Reused from Sanitation	Agriculture		Excreta	12.9	***59***	***37.9***	
Agriculture	NHx in atmosphere	18%	Agriculture	30.2	30.2	30.2	The global average percentage of N loss as NH3 was 17.6%, which is comparable to the range of 10-14% reported by the IPCC. [60]
Agriculture	N2 in atmosphere	19%	Agriculture	33.2	33.2	33.2	The ratio of denitrification (N2) (48 Tg N per yr), NOx emission (2 Tg N per yr), and N2O emission (7 Tg N per yr) to total N inputs (248 Tg N per year) [61]
Agriculture	NOx in atmosphere	1%	Agriculture	1.4	1.4	1.4	
Agriculture	N2O in atmosphere	3%	Agriculture	4.8	4.8	4.8	

Agriculture	Unknown	3%	Agriculture	5.3	5.3	5.3	Calculated as the difference of Nr in atmosphere, NHx in atmosphere, and denitrified N-species in atmosphere.
Crop Uptake	Food	85%	Crop Uptake	71.3	71.3	71.3	An estimated 15% in metabolic losses in animal feeding; waste and spillage during food processing and retail [62]
Crop Uptake	Food Loss	15%	Crop Uptake	12.6	12.6	12.6	
Food Loss	NOx	4%	Food Loss	0.5	0.5	0.5	100% of food loss assumed to be released to the atmosphere as NH_3 and NOx; ratio of NH_3 and NO_x determined from values of “21.6 x 10^6 ton N per year as NH_3 emissions” to “818 Gg N_2O (projected for 2020)” given to produce livestock [63]
Food Loss	NHx	96%	Food Loss	12.1	12.1	12.1	
Food	Excreta	97%	Food	69.2	69.2	69.2	97% of N in food excreted as urine and faeces; the remaining 3% of N in food excreted as sweat, hair, and blood [35]
Food	Unknown	3%	Food	2.1	2.1	2.1	
Excreta	Sewered	40%	Excreta	21.4	***0***	21.4	More than 60% of the global population lacks access to safely managed sanitation services, which is defined as access to a sanitation facility at the household where excreta is safely treated. 31% of the global population uses sanitation facilities connected to sewers. [22], [25], [33]
Excreta	Nonsewered	60%	Excreta	47.7	***0***	***9.8***	
Excreta	Agriculture (with max nitrogen recovery)	86%	Excreta	0	***59.5***	***32.6***	86% of the nitrogen in excreta is recovered in a household latrine vault. The remainder is assumed to be volatilized as atmospheric NH_3. [45]
Excreta	NHx (with EcoSan)	14%	Excreta	0	**9.7**	***5.3***	
Nonsewered	NHx	20%	Nonsewered	9.5	***0***	***2.0***	20% of N from human excreta lacking a sewage connection is lost as NH_3. 20% of N recycled from excreta. Remainder of N from non-sewered human excreta is assumed discharged to surface water [35]
Nonsewered	Agriculture	20%	Nonsewered	9.5	***0***	***2.0***	
Nonsewered	NO3/NH4 in Waterways	69%	Nonsewered	28.6	***0***	***5.9***	
Sewered	NO3/NH4 in Waterways	10%	Sewered	2.1	***0***	***2.1***	In the referenced study: of the estimated 4.7 kg of nitrogen per capita per year flowing through a
Sewered	Sludge	30%	Sewered	6.4	***0***	***6.4***	

Sewered	N2O in Atmosphere	2%	Sewered	0.2	***0***	***0.2***	household blackwater treatment system managed by a centralized wastewater treatment plant, 2.8 kg is denitrified to atmosphere N_2, 1.4 kg is mineralized in sludge, 0.079 is denitrified to N_2O in sewers, and the remainder is discharged as liquid effluent [36]
Sewered	N2 in Atmosphere	60%	Sewered	12.8	***0***	***12.8***	
Sludge	Agriculture	53%	Sludge	3.4	***0***	***3.4***	Australia applies approximately 55% of biosolids produced to agricultural land in [39]; Europe applies 63% of its biosolids to agriculture (or it is composted and then applied to agriculture) [41]; 41% of biosolids in the U.S. are land-applied [40]; and estimated 53% of Canada's biosolids are land-applied [38].
Sludge	Unknown	47%	Sludge	3.0	***0***	***3.0***	
NO3/NH4 in Waterways	N2O in atmosphere	76%	Of N2O in Atmosphere from Nr in Agriculture	3.7	***1.1***	***1.7***	Calculated from the ratio of 1.6 Tg per year (indirect emissions from nitrogen leaching and runoff) to 2.1 Tg per year (direct soil emissions) [19]
NO3/NH4 in Waterways	N2 in atmosphere	See note with reference.		31.0	***9.0***	***14.7***	More than 80% of nitrogen in waterways denitrified (to N2O or N2). Calculated as 80% of the nitrogen incoming less the contribution to N2O
NO3/NH4 in Waterways	Unknown			8.7	***2.5***	***4.1***	Assumed to either be volatilized as NH_3 or to contribute to eutrophication

The estimated loss of nitrogen to the environment is calculated below in Table 4. The loss of nitrogen from the total agriculture-sanitation system is calculated from the ratio of nitrogen reused in agriculture to total nitrogen used in agriculture (i.e. whatever is not reused in agriculture is lost to the environment). Similarly, the loss of nitrogen from the agriculture sub-system (defined as those processes between application of nitrogen in fertilizer and nitrogen in food) is calculated from the ratio of nitrogen in food to total nitrogen used in agriculture (i.e. whatever nitrogen is not transformed to food is lost to the environment). The loss of nitrogen from the sanitation system is calculated as the difference between the nitrogen lost in the agriculture-sanitation system and the agriculture sub-system.

Table 2-4 Estimate of nitrogen loss to the environment within the agriculture and sanitation system.

(Sub-)System	Calculated As	Estimated nitrogen loss to the environment in 2010
Agriculture and Sanitation	1 – (Nitrogen Reused in Agriculture / Total Nitrogen in Agriculture)	92%
Agriculture	1 – (Nitrogen in Food / Total Nitrogen in Agriculture)	55%
Sanitation	(Nitrogen Loss in Agriculture & Sanitation) – (Nitrogen Loss in Agriculture)	37%

3. Measurement and modelling of moisture sorption isotherm and heat of sorption of fresh faeces

3.1. Abstract

The drying (or dewatering) of fresh faeces and faecal sludge is a productive step in the management of sanitation, waste treatment, and resource recovery services. An improved understanding of fresh faeces and faecal sludge drying would contribute to the development and deployment of faecal sludge management services. However, there is an observed lack of available literature on the fundamental drying characteristics of fresh faeces. In response to this gap, this work shares experimental results for equilibrium moisture content of fresh faeces at different water activity (a_w) and proposes the use of the Guggenheim, Anderson, and de Boer (GAB) model for predicting a_w, calculating the heat of sorption, and estimating the corresponding energy requirements for drying of fresh faeces. In addition to informing drying process design, the sorption isotherm can be used to predict microbial activity, which could improve the management of faeces and faecal sludge from a public health perspective. These data in turn will be used to promote access to dignified, safe, and sustainable sanitation.

3.2. Introduction

Effective sanitation, waste treatment, and resource recovery systems are central when it comes to the protection of human health, prevention of environmental degradation, and reclamation of valuable resources. An estimated 61% of the global population, or 4.6 billion people, is without access to household-level sanitation and waste treatment where excreta is contained and treated [4]. Excreta that is unsafely managed can leach into the environment, polluting surface water and groundwater. This has significant public health consequences: about 88% of all diarrheal deaths are attributed to inadequate WaSH systems and diarrheal disease caused over 71 million DALYs in 2010 [6], [7]. This global sanitation crisis is “rooted in aspects of poverty, power, and inequality” [64]. Prioritizing universal access to effective sanitation systems is an issue of equity with far-reaching implications: the poorest households are least able to invest in their own sanitation systems and are the most vulnerable to adverse public health, and consequently socioeconomic, outcomes associated with ineffective sanitation systems [65].

Drying is a complex, multi-equilibrium process, and numerous models with varying degrees of sophistication have been developed to simulate the process. Models are used to inform and optimize design and control of process conditions [66]–[68]. There has been initial research on faecal sludge drying including calculating the energy requirements for dewatering pit latrine sludge to determine the overall energy balance associated with the production of solid fuel char briquettes from excreta [69]**.** Drying is a crucial step in any thermal treatment process. It has been estimated that more than 95% of the energy required for produce char from feces is used in drying faeces [70] and 50% of the heat required from fuel could be sufficient for all pre-drying, drying, and pyrolysis steps [71]. Drying is driven by the difference between the thermodynamic activity of water as vapour in the atmosphere and water as moisture in the wet solid. However, there is no published literature for three key thermodynamic characteristics – moisture sorption isotherms (MSI), heat of sorption, and energy requirements for drying – or a widely-accepted model that estimates these parameters for fresh faeces.

MSIs are a graphical representation showing the evolution of the moisture content within a specific material vs. water activity (a_w) [72]. a_w is equated to relative humidity when relative humidity is fixed within the atmosphere; it is defined as the ratio of a material’s vapor pressure to distilled water vapor pressure under the same temperature and humidity conditions [73]. Water activity is a thermodynamic property used to describe the availability of water within a material. Sorption isotherms describe the change in a sample’s moisture content in relation to the thermodynamic activity of the water at a fixed temperature [74]. The relationship between moisture content and a_w is determined by chemical composition, or by the availability of polar sites for the binding of water molecules [73]. The moisture content and chemical composition of fresh faeces varies with factors like vegetarian vs. non-vegetarian diet, fibre content of diet, age, and health conditions [34]. MSIs are used to calculate the isoteric heat of sorption for estimates of drying times and energy requirements.

An improved understanding of the thermodynamic properties of fresh faeces drying has important ramifications. Water activity describes the degree to which moisture is bound within a solid and subsequently its availability to participate in physical, chemical, and microbiological reactions [75]. Understanding water activity and the thermodynamic properties of fresh faeces and faecal sludge are important in the design and optimization of drying operations based on a rational understanding of the food-solid interactions [75]. Drying is an important treatment mechanism from both a public health and operational perspective. Most pathogenic bacteria are inactivated by moisture reduction to below a water activity, a_w, of 0.85 [72], [76]. Drying can therefore assist in pasteurizing and sanitizing fresh faeces, which can minimize the public health risks associated with managing the waste collected in onsite sanitation systems and for other faecal sludge management processes. Additionally, drying of fresh faeces can reduce costs related to transportation and storage by decreasing the mass and volume of the material [77]. Finally, drying is a critical step in resource recovery methods such as compost production [78], fuel production [79], and production of building materials [77].

This work builds on exploratory research performed by Bourgault et al. that justified the use of MSI to derive fundamental characteristics for faecal sludge [80]. In addition to validating the approach explored by Bourgault et al., this work evaluates the moisture sorption isotherm of fresh faeces at three different temperatures with the objective of calculating the isoteric heat of sorption, a value that can be used to predict the energy requirements of drying.

3.3. Materials and Methods

Fresh faeces samples were prepared and initially characterized (pH, conductivity, COD, and moisture content). Equilibrium moisture content of the fresh faeces samples were determined via a static gravimetric analysis, and MSIs were then modeled using non-linear least squares regression analysis. The heat of sorption for fresh faeces was then calculated using the best-fitting model (as defined by the given statistical criteria described below).

3.3.1. Sample preparation and initial characterization

Fresh faeces samples were provided by healthy consenting volunteers (n=6). Ethical approval was obtained from the UVic Human Research Ethics Board (HREB) prior to recruiting volunteers and procuring samples (Protocol Number 18-187). Volunteers were recruited from UVic (Victoria, Canada). Samples were procured and all initial characterization was completed within three hours of defecation.

Collected samples were gently homogenized, and an initial characterization of the pH, chemical oxygen demand (COD), conductivity, and initial moisture content of the sample was performed. For determination of pH and electrical conductivity of faeces, 1:400 m/v suspension with deionized water was made. The typical approach to measuring the pH and conductivity of fresh faeces is to measure a homogenized sample rather than a sample in suspension [81]–[84], but the 1:400 suspension method was followed for consistency with exploratory work performed by Bourgault et al. [80].

pH and electricity conductivity were determined with an HQD Portable Meter and Probe (HACH, USA) (sensitivity of ±0.02 pH units; ±1 μS/cm, respectively) by immersion of the probe in the suspension. The moisture content analysis was performed using the oven method at 105˚C after final equilibrium mosture content was reached [85]. COD analysis was measured spectrophotometrically (sensitivity of ±14 mg per L) using the reactor digestion method as per manufacturer's instruction (HACH method 8000 [86]). Characterization occurred within 2 hours of defecation.

3.3.2. Equilibrium moisture content determination

Equilibrium moisture contents of fresh faeces were determined experimentally in the PH2E Lab of UVic using the static gravimetric analysis proposed by Bourgault et al. in the study of faecal sludge [80]. This method has been validated as a technique to measure water distribution within waste activated sludge [68].

Seven saturated salt solutions were prepared corresponding to a range of water activities from 0.06 to 0.97 [87]. Each solution of 100 mL was poured into separate glass jars (i.e. experimental chambers) fitted with a polyethylene foam support to hold the fresh faeces sample (Figure 3-1). A capillary tube of thymol was also placed in each jar to inhibit microbial growth, as per previous work [14]. Triplicate samples of about 1.5 g of fresh faeces were weighed in aluminium crucibles and placed on supports in each jar which were then tightly closed and hermetically sealed with vacuum grease. Samples were spread on the crucible such that each had approximately the same surface area. The isotherm analysis began within 3 hours of defecation. The samples were then placed in Peltier Incubators (VWR, Canada) at 15˚C, 25˚C, and 35˚C for equilibration. Each temperature-humidity combination was analyzed in triplicate. Specific experiments were also replicated with different sample masses (1.0 g, 1.5 g, and 5.0 g) and different sample donors to determine if sample mass or source of fresh faeces sample had a statistically significant impact (α=0.05) on the equilibrium moisture content.

Figure 3-1 Each experimental chamber was prepared with 100 mL of saturated salt solution, a (blue) support (on which the sample was placed), and closed tightly with vacuum grease. A capillary tube of thymol was also placed in each jar to inhibit microbial growth.

The required equilibration time was about 15 days based on the change in weight (dry basis) weighed at regular intervals (24 hours) until the weighed mass varied by less than 2% for two consecutive weighings. The samples were weighed daily using a Sartorius QUINTIX Analytical Balance with an accuracy of 0.001 g. The dry mass content was determined by oven drying at 105˚C for 24 hours. The equilibrium moisture content was calculated on dry basis from the equilibrium mass and dry mass content (Eqn. 1 below).

$$x = \frac{(m_f - m_i) + \left[\frac{\%H_2O}{100} \cdot m_i\right]}{m_i \cdot \left[\frac{100 - (\%H_2O)}{100}\right]} \qquad \text{(Eqn. 1)}$$

x = equilibrium moisture content (g water/g dry)

m_f = final weight of sample at equilibrium

m_i = initial weight of same sample

$\%H_2O$ = wet basis % moisture content of the wet sample

3.3.3. The analysis of correlation between equilibrium moisture content with initial characterization data and the multiple linear regression analysis of the effect of temperature, humidity, sample mass, and donor on the equilibrium moisture content

To test the correlations between the initial moisture content and the other initial characterization data (COD, conductivity, and pH), a Pearson product-moment correlation coefficient was calculated (n = 7).

A multiple linear regression was applied to analyse the effect of temperature, humidity, sample mass, and donor on the equilibrium moisture content and determine which variables were significant. This served as a preliminary evaluation as to whether the data could be used to model a MSI for fresh faeces. MSI do vary by temperature and humidity, but significant variation between donors (or the other independent variable, sample mass) might indicate that the data was too variable to generate a single MSI for fresh faeces. The predictor variable "donor" is categorical and was transformed into a set of n-1 separate binary variables (i.e. "dummy coding"). The remaining predictor variables are continuous. The multiple linear regression model (Eqn. 2) consisted of:

$$x = \beta_0 + \beta_1 \cdot Temperature + \beta_2 \cdot Humidity + \beta_3 \cdot Sample\ Mass + \beta_4 \cdot Donor + \varepsilon \quad \text{(Eqn. 2)}$$

where β_0, β_1, etc. are regression coefficients and temperature, humidity, sample mass, and donor are various factors that may impact the equilibrium moisture content. The p-values associated with the individual factors were used to determine whether the factors were significant.

Both the Pearson coefficients and the multiple linear regression were computed in the R development core system [88]. Results were interpreted using a significance level $\alpha=0.05$.

3.3.4. Modelling of MSI

The experimental data was fitted to models by 1) estimating parameters for each temperature considered, and then 2) estimating parameters with the use of modified model versions that consider temperature dependence. The fit and prediction quality of the models were analyzed by the root mean squared error (RMSE) (Eqn. 3), mean absolute percentage error (MAPE) (Eqn. 4), and residual standard error (RSE) (Eqn.5); residuals are calculated as $(\widehat{y_i} - y_i)$ (or the difference between the observed value and the value predicted by the model) [89].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\widehat{y_i}-y_i)^2}{n}} \qquad \text{(Eqn. 3)}$$

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i-\widehat{y_i}}{y_i}\right| \qquad \text{(Eqn. 4)}$$

$$RSE = \sqrt{\frac{\sum_{i=1}^{n}(\widehat{y_i}-y_i)^2}{v}} \qquad \text{(Eqn. 5)}$$

The table below lists the mathematical isotherm models used in model fitting (Table 3-1). There are several mathematical models that are used to describe the sorption isotherms of food materials. It is necessary to test several models because no one equation is accurate for all materials for the complete range of water activities because the way water is distributed within a solid is by different mechanisms in different water activity regions [75]. Models were selected based on their use in describing biological materials with a higher moisture content [68], [73], [80]. Different models are most effective in describing the sorption isotherm at different a_w levels as shown in the table below [73], [90], [91].

Table 3-1 Selected isotherm models for fitting experimental data. The monolayer water content (X_m) is assumed to be temperature independent and indicates the number of sorption sites available on the surface of the material. Different models are used to describe the MSI at different a_w ranges (shown as "a_w Range") and model fitting was done with a subset of the data associated with the referenced a_w range.

No.	Reference	Model	a_w Range	Equation

1	[73]	Brunauer-Emmett-Teller (BET)	$a_w < 0.5$	$X = \frac{X_m A a_w}{(1-a_w)[1+(A-1)a_w]}$
2	[89]	Chin	$0 < a_w < 1$	$X = \frac{A}{\ln a_w} + B$
3	[80]	Flory-Huggins	$0 < a_w < 1$	$X = A\, e^{B a_w}$
4	[73]	GAB	$0.03 < a_w < 0.95$	$X = \frac{X_m B A a_w}{(1-A a_w)[1+(B-1)A a_w]}$
5	[73]	Lewicki (2-parameter)	$0 < a_w < 1$	$X = A\left[\frac{1}{a_w} - 1\right]^{b-1}$
6	[73]	Oswin	$0 < a_w < 1$	$X = A\left[\frac{a_w}{1-a_w}\right]^{B}$
7	[73]	Smith	$0.5 < a_w < 0.95$	$X = A + B\log(1-a_w)$
8	[90]	Halsey	$0 < a_w < 1$	$X = \left(\frac{-A}{RTln(a_w)}\right)^{1/B}$
9	[68]	Modified Chung Pfost	$0 < a_w < 1$	$X = \frac{-1}{A} \cdot \ln\left(-\ln(a_w) \cdot \frac{T+B}{C}\right)$
10	[91]	Modified Oswin	$0 < a_w < 1$	$X = (k_1 + k_2 \cdot T)\left(\frac{a_w}{1-a_w}\right)^{(k_3 + k_4 \cdot T)}$

The parameters of the models were determined using non-linear least squares regression analysis in the R development core system [88]. To evaluate the ability of each model's fit to the experimental data, the RMSE, MAPE, and RSE were computed.

3.3.5. Determination of heat of sorption from the MSI

The heat of sorption was calculated based on the model with the best fit to the experimental data over the entire a_w range (i.e. the lowest RMSE, lowest MAPE, and lowest RSE). Generally, a MAPE of less than 10% justifies the use of the model for describing experimental data; and low values of RMSE and RSE are expected for models that adequately describe the data [73].

$$\ln(a_w) = -\frac{\Delta H}{R}\frac{1}{T} + constant \quad \text{(Eqn. 6)}$$

The heat of sorption was calculated following established methods [68], [73], [92]. Equation 6 is derived from the Clausius-Clapeyron equation where ΔH is the heat of sorption, R is the gas constant (8.3145 J/mol K), and T is the temperature in Kelvin [68].

Using the best-fitting MSI model, a_w can be estimated for a given moisture constant. The slope of the plot of $\ln(a_w)$ vs. 1/T can then be used to calculate the heat of sorption. The mathematical relationship between the heat of sorption and the equilibrium moisture content was fitted in the R development core system using nonlinear least squares method. Confidence bands for the relationship were generated using an error propagating function [93]. The fitted relationship was used to estimate energy requirements for drying.

3.4. Results and Discussion

For the given samples, the pH was 7.7 ± 0.3 (the average ± standard deviation) and the conductivity was 86 ± 19 µS/cm (the average ± standard deviation). Results from the initial COD and moisture content characterization analysis are summarized in Table 3-2 and compared with literature values.

Table 3-2 Comparison of results from characterization of fresh faeces samples (n=7) with literature values. When available, values given as averages ± standard deviation.

Characteristic	Result	Comparison to literature values	
		Rose et al. [34]	Bourgault et al. [94]
COD (mg per g dry faeces)	1366 ± 106	567 to 1450	1395 ± 293
Moisture content (%)	76 ± 5%	63% to 86%	80 ± 3%

Both the measured COD and moisture content are within the ranges reported in Rose et al. and Bourgault et al. The values reported by Rose et al. represent a survey of 47 samples. Variation in moisture content is attributed to differences in fibre intake: individuals with vegetarian diets will have a higher moisture content than those who consume less fibre and more protein [34]. Similarly, COD is used to measure the bulk organic content of faeces; this depends on dietary intake and its biological availability [34]. The narrower range measured in this analysis may indicate that the samples in the study are limited with respect to geographical and dietary representation.

Initial moisture content was correlated with COD (Pearson's correlation coefficient = -0.92, $p < 0.01$) and conductivity (Pearson's correlation coefficient = -0.97, $p < 0.01$). Initial moisture content was poorly correlated with pH (Pearson's correlation coefficient = 0.23, $p = 0.62$). From a qualitative perspective, many samples were observed to have undigested food particles and there was variation in both odor and texture.

Both temperature and humidity have a significant impact on equilibrium moisture content at a significance level of $\alpha = 0.05$ (Table 3-3). This is expected: equilibrium moisture content represents a solid's moisture content at the thermodynamic equilibrium given relative humidity and temperature conditions [74]. Neither the sample mass nor the donor have a significant impact on equilibrium moisture content at a significance level at $\alpha = 0.05$ (but donor does have a significant impact on equilibrium moisture content at a significance level at $\alpha = 0.10$). This finding should be caveated with the note that analysis is based on a small sample size.

Table 3-3 Summary of regression coefficients for multiple linear regression model (Eqn. 2) (ANOVA, F(4, 394) = 39.38, P value < 0.01) relating to equilibrium moisture content with the factors of temperature, humidity, sample mass, and donor.

Variable	Estimate	Std. Error	Significance (p-value)
Intercept	0.19	0.18	0.28
Temperature	-0.010	0.0048	0.034
Humidity	1.33	0.11	> 0.001
Sample Mass	-0.0065	0.063	0.92
Donor1	-0.21	0.14	0.14
Donor2	0.24	0.14	0.099
Donor3	0.062	0.22	0.78
Donor4	-0.19	0.11	0.074

Equilibrium moisture content of fresh faeces at three temperature levels of 15˚C, 25˚C, and 35˚C in the range of 6-97% relative humidity values are shown in Figure 3-2. Most samples required 2-4 weeks to reach equilibrium. The isotherm curves demonstrate a roughly sigmoid shape and there is a general decrease in equilibrium moisture contents with increasing temperature. The range of values at higher relativity humidity values is greater because at a relative humidity of 100%, the sorption isotherm tends to a vertical asymptote, which causes an increased variance at higher relative humidity.

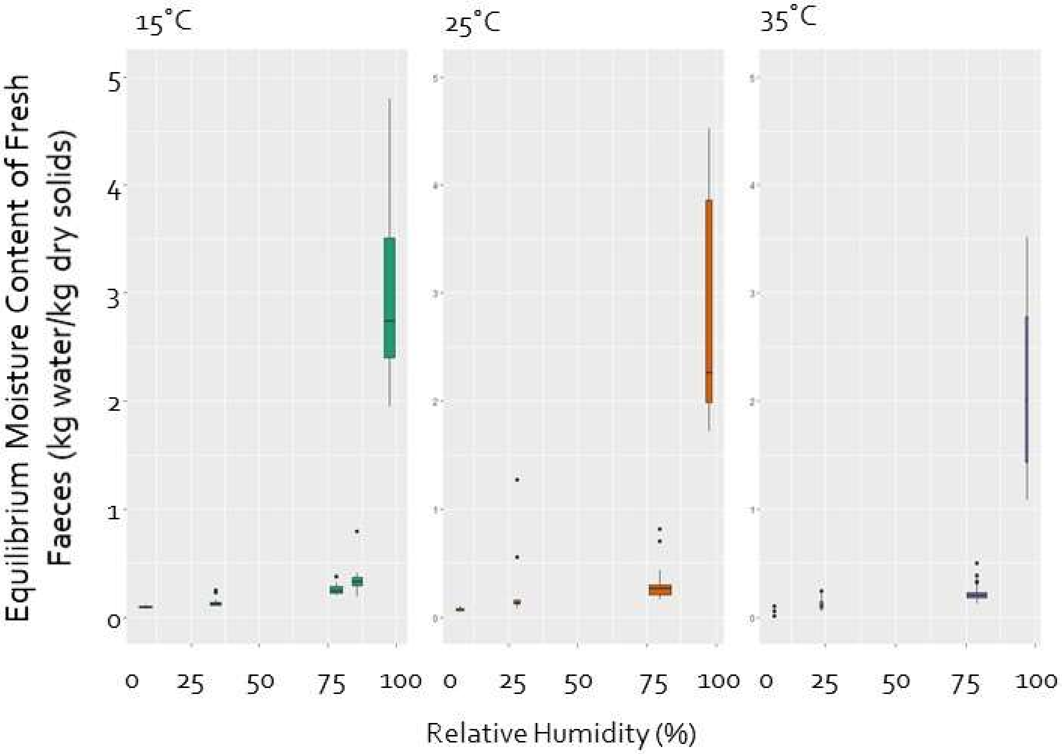


Figure 3-2 Box plots of equilibrium moisture content data at temperatures of 15˚C, 25˚C, and 35˚C with a sample mass of 1.5 g. The data suggests a sigmoidal sorption isotherm with two inflection points. At a relative humidity of 100%, the sorption isotherm tends to a vertical asymptote, which causes an increased variance at higher relative humidity.

Equilibrium moisture content depends on the nature of the given solid in addition to the operating conditions. Sorption isotherms give an indication of the binding mechanism of moisture in sludge [95]. In general, it can be seen in Figure 3-2 that at a higher temperature, the equilibrium moisture content that corresponds to a given water activity is lower. Equilibrium moisture content has been considered as a parameter to characterize water distribution: whether it is chemically bound, internal water, or intracellular water [74]. The pattern of the sorption isotherm depends on the temperature and water-solid interactions [74], [76]. Table 3-4 shows the parameter estimates as well as the calculated error criterion (Eqn.'s 3-5) for various models used to describe sorption isotherms.

Table 3-4 Model fit coefficients and error criterion

Model	Temp (˚C)	P-values for the Model Fit Coefficients					RMSE	MAPE	RSE
		X_m A	A	B	C	D			
BET	15	<0.01	0.53				0.027	0.127	0.619
	25		0.83				0.184	0.259	0.956
	35		<0.01				0.036	0.365	0.600
Chin	15		<0.01	0.97			0.442	0.456	0.130
	25		<0.01	0.59			0.363	0.384	0.171
	35		<0.01	0.94			0.305	0.443	0.160

Flory-Huggins	15		0.63	<0.01			0.448	0.687	0.133
	25		0.46	<0.01			0.375	0.654	0.181
	35		0.36	<0.01			0.308	0.624	0.163
GAB	15		<0.01	0.76			0.067	0.137	0.320
	25		<0.01	0.84			0.157	0.241	0.787
	35		<0.01	<0.01			0.046	0.269	0.275
Lew	15		0.03	0.57			0.441	0.536	0.129
	25		<0.01	0.73			0.365	0.554	0.173
	35		<0.01	0.497			0.304	0.523	0.160
Oswin	15		0.03	<0.01			0.441	0.536	0.130
	25		<0.01	<0.01			0.365	0.554	0.173
	35		<0.01	<0.01			0.304	0.523	0.160
Smith	15		0.33	<0.01			0.093	0.149	0.730
	25		0.61	0.24			0.120	0.215	0.966
	35		0.09	<0.01			0.050	0.156	0.681
Halsey	all		<0.01	<0.01			0.366	0.462	0.149
Modified Chung Pfost	all		<0.01	<0.01	0.04		0.652	2.77	0.475
Modified Oswin	all		0.01	0.02	0.32	0.05	0.364	0.545	0.148

A: The data and model for BET at 15˚C (based on the statistical criteria) were used to derive the monolayer constant used in the BET and GAB equations.

The Smith, GAB, and BET models provided the best fit to the experimental data for their respective a_w ranges, but the GAB model provides the best fit to the experimental data on the entire a_w range when considering all three error criterion and an expected increase in equilibrium moisture content with increased temperatures (Figure 3-3). The Smith model coefficients did not demonstrate the expected increase in equilibrium moisture content with decreasing temperature. The GAB model has been reported to give a good fit for over 75% of food isotherms: starchy foods, fruits, vegetables, and meat products [75]. Given that faeces will be most like food in terms of molecular composition, it makes sense that the GAB model fits well.

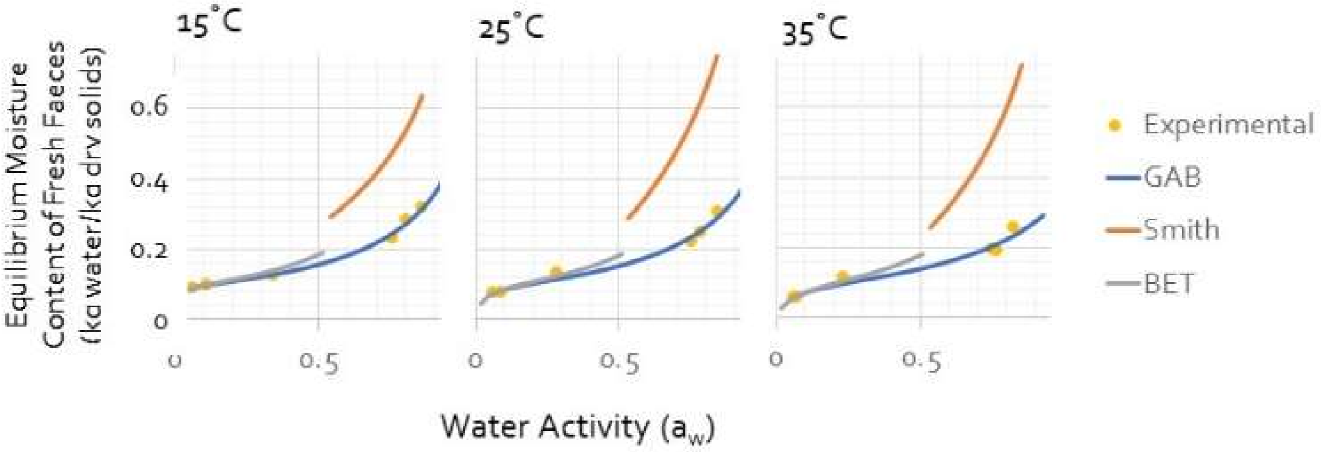


Figure 3-3 Comparison of predicted sorption isotherm curve for fresh faeces using the BET, GAB, and Smith models with experimental equilibrium moisture contents. The dots represent the experimental average. The GAB model was fitted to the entire activity range and both the Smith and BET models were fitted to the activity range that they are used to describe (Table 3-2)

The heat of sorption is calculated from the plot of ln(a_w) vs. 1/T with the GAB model (Figure 3-4). The total heat of evaporation is significant up to a moisture content of about 0.2 kg water per kg dry solids (at this moisture content, the curve becomes asymptotic (Figure 3-4)).

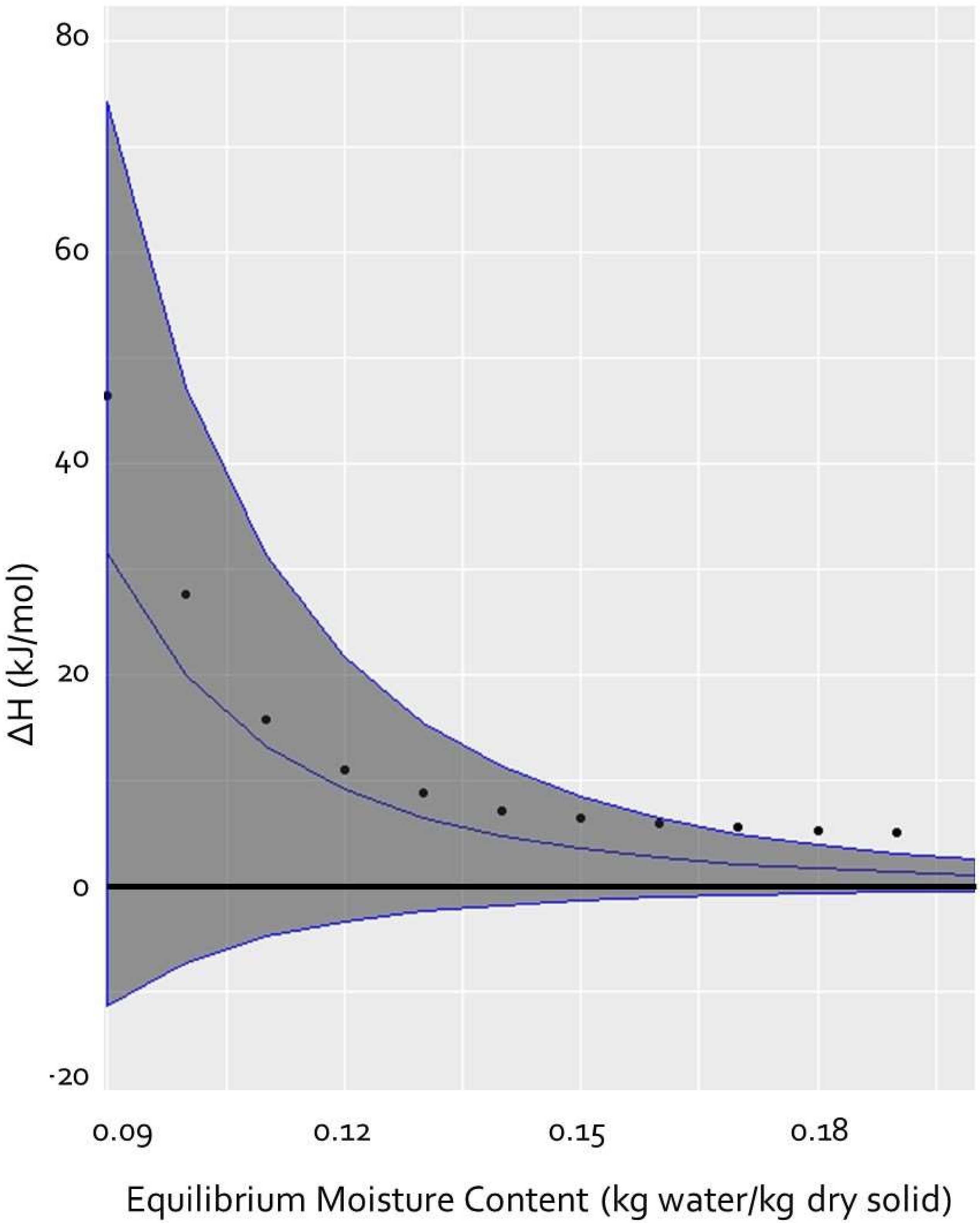


Figure 3-4 Heat of sorption of fresh faeces versus moisture content; calculated with the GAB equation. The relationship between heat of sorption and equilibrium moisture content (x) was fitted as ΔH =

$0.001505(x)^{-4.277039}$ using nonlinear least squares method in R. Confidence bands on the relationship were generated using an error propagating function.

The heat of sorption is important when designing equipment for the drying and dewatering process [75]. As can be seen in Figure 3-4, the heat of sorption decreases as the moisture content increases. This suggests that an increasing amount of energy is required as moisture content of fresh faeces and dryers should be designed to account for the differing degree to which water is bound to the solid and thus how much energy is required to remove it. More significantly, it may be of interest to design dryers for an intended final water activity that achieves a given treatment goal. For example, evaporation that results in desiccation or dehydration inactivates pathogen; although some yeast and eggs survive in drier conditions, many faecal-borne pathogens cannot survive at a water activity of less than 0.9 [77].

Most pathogens are inactivated at a_w lower than 0.85 [6]. For the given data and analysis performed in this experiment, an a_w of 0.85 corresponds to a moisture content of 27% to 34% over a temperature range of 15˚C, 25˚C, and 35˚C. Given an anticipated range of initial moisture contents of 63 to 86% [94], this translates to an estimated energy requirement of 0.05 to 0.4 kJ/mol (Table 3-5).

Table 3-5 Calculation of the energy requirements for drying fresh faeces from an initial moisture content of 63% to 86% to the moisture content corresponding to a_w of 0.85 at a temperature range of 15˚C to 35˚C. The relationship between a_w and moisture content calculated using the GAB relationship and the relationship between moisture content and the heat of sorption calculated with the fitted relationship described in Figure 3-4.

	a_w	Moisture content	Drying energy requirements
Initial	0.93 to 1	63% to 86%	**0.05 to 0.40 kJ / mol**
Pathogen inactivation	< 0.85	27% to 34%	
Difference	0.08 to 0.15	29% to 59%	

However, this analysis of energy requirements is based on a limited set of data that has enough variability to be non-representative of fresh faeces as a generalizable matrix. It is still required to investigate the a_w characteristics of faecal sludge to develop technologies and processes for faecal sludge management beyond the initial containment (and treatment) of fresh faeces.

There are no data available regarding the energy requirements for drying fresh faeces. There is some literature that discusses the energy requirements of dewatering sewage and pit latrine sludge as a pre-pyrolysis step in the production of biochar [96], [97]. However, these studies consider only the energy requirements of the dewatered sludge as the drying step is performed by a variety of technologies where energy requirements remain unmeasured [71]. These studies do acknowledge that pretreatment (i.e. drying) is a critical processing step as human faeces as a high moisture content.

Since there are no readily available energy values available for comparison, the following is a comparison of the equilibrium moisture content of fresh faeces measured in the study with that measured by Bourgault et al. for faecal sludge and by Vaxelaire et al. for waste activated sludge.

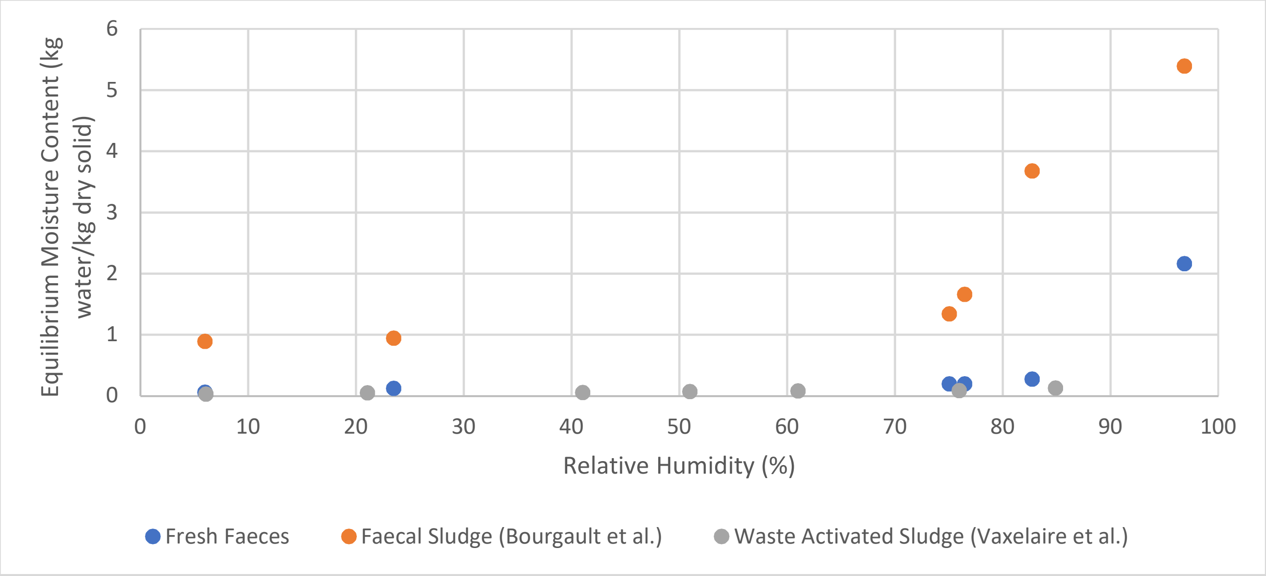


Figure 3-5 Comparison of equilibrium moisture content of fresh faeces at 35˚C (measured in the present analysis), faecal sludge 35˚C [80], and waste activated sludge at 39˚C [68].

The values of equilibrium moisture content for the three matrices described in Figure 3-5 are on the same order of magnitude. Variation between the values can be attributed to a combination of temperature (the values for equilibrium moisture content for waste activated sludge were evaluated at 39˚C compared to 35˚C for fresh faeces and faecal sludge) and chemical composition. Bourgault et al. concluded from the data that water in fresh faeces appears to be more easily extracted from a water activity of 1 to 0.75 (corresponding to a relative humidity of 100% to 75%) [80]. The water corresponding to this range of water activity may correspond to "free water." Free water is that moisture within the solid that exists with unhindered mobility [75]. In comparison, it appears that the bound water in fresh faeces corresponds to a higher water activity range (greater than 85%). The variation in bound or unbound water is dependent on water-solid interactions and is an inherent thermodynamic property.

Bourgault et al. evaluated the use of three models and concluded that the use of the GAB model is most appropriate for representing the sorption isotherm of faecal sludge [80]. The GAB model has been described as the most versatile sorption model and has a viable theoretical background based on principles of moisture's physical adsorption properties [75]. Vaxelaire et al. discussed that the GAB equation enables good modeling at a given temperature but has poor fitting when modeling at varied temperatures; Vaxelaire et al. instead justified the use of the Oswin model to describe the sorption isotherm of waste activated sludge based on selected statistical criteria [68]. The Oswin model is an empirical model that is recommended for describing the isotherms of starchy foods [75].

There is significant literature available to describe the dewatering and moisture distribution characteristics of conventional activated sludge. The methods used in wastewater can be applied to faecal sludge and fresh faeces moisture distribution characteristics. One method that has been identified in wastewater literature is the moisture sorption isotherm technique used in this study [74]. This study represents a significant advance towards producing the same key criteria for fresh faeces that exists for waste activated sludge using a method identified in the wastewater sludge.

According to the multivariable linear regression model, both temperature and humidity have a significant impact on equilibrium moisture content at a significance level of $\alpha = 0.05$ (Table 3-3). Neither the sample mass nor the donor are statistically significant. However, a variability in chemical composition – and therefore the a_w characteristics – would be expected in individual faeces samples (and even for a single individual over time), and it is possible that the lack of significance in this case is due to the limited sample size.

In response to this, it may be possible to develop a universal MSI by analyzing the chemical composition of fresh faeces' samples (or alternatively using COD measurements as a proxy for chemical composition). In other words, a MSI could be developed by understanding fresh faeces as a composite of chemicals. Moreira et al. developed a simple algorithm to predict the water sorption isotherm of fruits, vegetables, and legumes based upon chemical composition (i.e. protein, fibre, starch, glucose, fructose, sucrose, salt, and other) [98]. The advantage of a universal MSI for fresh faeces would be to support the development of a sanitation system capable of achieving in-situ pathogen inactivation objectives via drying.

The drying of fresh faeces and faecal sludge is a productive step in the management of sanitation and waste treatment services. One focus of recent research in sanitation engineering in low- and middle-income countries is the development of low resource-use technologies (e.g. the development of on-site sanitation systems that function without water) [99]. A recent study by Eekert et al. suggests that the performance of pit latrines could be improved with the addition of freshwater [100], [101], but in general there is a growing recognition of declining freshwater availability at the global and local scales and as such, waterborne sanitation systems are potentially advantageous in all contexts: low-, middle-, and high-income countries [100], [102], [103]. Additionally, the advantages of drying in faecal sludge management include increased pathogen inactivation [104] and the reduction of costs related to transport and treatment of faecal sludge [77]. An improved understanding of fresh faeces and faecal sludge drying contributes to the development and deployment of sanitation and waste treatment management services that are adaptive to shifting freshwater availability.

In general, fresh faeces and faecal sludge are matrices that have not been well-characterized from the perspective of improved sanitation, waste treatment, and resource recovery technological development and service provision [34], [94], [105]. This work contributes to an improved characterization of fresh faeces as well as an elaboration of an experimental technique that could be applied to faecal sludge. Future work includes comparing this data with faecal sludge from varied sources to compare the physical water distribution of fresh faeces with faecal sludge, integrating characterization data (e.g. COD) or chemical composition into MSI models, and determining the relationship between a_w and pathogen inactivation.

There is additional interest in investigating the applicability of this research to composting toilet designs (such as that discussed in Chapter 4). For example, this data could be used to investigate if composting toilet designs that operate by passive ventilation generate enough drying energy to achieve in situ pathogen inactivation objectives.

3.5. Conclusions

The objective of this work was to describe the MSI of fresh faeces and the corresponding energy requirements of drying. This data is useful in the design of systems and processes that treat and manage faeces by drying, but there is no information available in the literature. A static gravimetric analysis was used to derive experimental sorption isotherms at 15˚C, 25˚C, and 35˚C. The GAB equation best fit the experimental data over the entire a_w range and was used to derive the heat of sorption. The heat of sorption curve shows the heat of evaporation is significant up to a moisture content of about 0.2 kg water per kg dry solids.

4. The Exploration and Adoption/Preparation of a composting toilet system for the University of Victoria

4.1. Abstract

Composting toilets are a sustainable sanitation system with evidence-based advantages relative to conventional sewerage and other onsite sanitation systems. Additionally, composting toilets were recently formalized as an onsite wastewater system in BC However, the systematic uptake of composting toilets is slow. Here we evaluate the implementation of a composting toilet on the UVic campus using the EPIS (Exploration, Preparation/Adoption, Implementation, and Sustainment) framework to identify those factors that facilitate or impede implementation. We identified the following as factors that facilitated implementation in the Exploration and Adoption/Preparation phases: supportive and self-reinforcing research and outcomes, favorable adopter characteristics, and the technology's beneficial features. The next steps include the Implementation and Sustainment phases.

4.2. Introduction

The design of sanitation and waste treatment systems is intimately connected to the greatest sustainability challenges of our time [43]. In many ways, composting toilets are an established technology with the potential to better conserve water and energy use, steward biochemical cycles (e.g. nitrogen, phosphorous), manage micropollutants found in excreta, and minimize greenhouse gas emissions [36], [51], [106], [107]. Despite the evidence of these advantages, the dissemination and implementation of composting toilets is slow [108]. The systematic uptake of evidence-based practices, like composting toilets, that provide an overall improved management of ecosystem services and public health can be studied to promote improved dissemination and implementation [109]. A widely-used framework to assess the dissemination and implementation of evidence-based practices is the Exploration, Adoption/Preparation, Implementation, and Sustainment (EPIS) framework [110].

Here we applied the EPIS framework to the installation of a composting toilet system on the UVic campus. At the time of writing (November 2019), the following phases of dissemination and implementation are complete: Exploration and Adoption/Preparation. The Implementation phase is planned for early 2020 and the Sustainment phase will be ongoing post-Implementation. In their analysis of research methods in WaSH, Setty et al., identified the relevance of dissemination and implementation research methods in answering the questions: "How can we (often actively) facilitate spread of the intervention? Who or what influences spread of the intervention?" [111]. Here we found the following factors facilitated the implementation of a composting toilet in the Exploration and Adoption/Preparation phases: research and outcomes supporting the composting toilet, key characteristics of the system adopters, and beneficial features of the composting toilet.

4.3. Composting toilet systems as an evidence-based practice

Composting toilets are a type of on-site sanitation system that operate without flush water and are designed to recover the nutrients in excreta for agricultural reuse [106]. On-site sanitation refers to all those sanitation systems that are not connected to sewerage systems but instead entail the containment of excreta on-site prior to treatment [112]. Common examples of on-site sanitation systems are pit latrines and septic tanks. When compared to onsite and sewered sanitation systems, composting toilets have the following advantages:

- Composting toilets have the potential to recover up to 86% of the nitrogen in human excreta for reuse in agriculture. In comparison, the combination of other onsite and sewered sanitation systems recover an estimated 23% of the nitrogen in human excreta. By recovering the nitrogen in excreta for agriculture use, there is decreased discharge of nitrogen to the environment thereby mitigating disruption to the nitrogen cycle, averting impact to biodiversity in aquatic environments, and mitigating greenhouse gas emissions associated with the agriculture-sanitation system. (“*2. The potential impact of ecological sanitation on the nitrogen cycle.”*)

- Similarly, composting toilets have the potential to recover 100% of the phosphorous in human excreta compared to the estimated 0-55% currently being recovered by the world’s combination of onsite and sewered sanitation systems [22], [45].
- Conventional water management infrastructure was built assuming long-term abundance and consistency of water resources, assumptions that are now acknowledged to be patently untrue [113]. It is estimated that over a quarter of household freshwater use in the U.S. is for flushing toilets [114]. In comparison, composting toilets use no water [106].
- Septic tank systems and conventional wastewater treatment plants are major input sources of chemicals of emerging concern to the aquatic environment with potentially significant impact on surface water, groundwater, and drinking water supplies with risks to public and environmental health [115]–[117]. In comparison, composting is effective for the treatment of CECs: temperature appears to be the most significant factor [118], [119].

In summary, composting toilets are more sustainable with regard to many of the planetary challenges of our time: freshwater scarcity, disruption of the nitrogen and phosphorous cycle, chemical pollution, biodiversity loss, and climate change. In the short-term, there could be a co-existence of composting toilet and waterborne sanitation systems. In the long-term, water-borne sanitation systems should be replaced at end of lifetime with innovative alternatives that perform better with regard to long-term sustainability.

4.4. The regulatory environment for composting toilet systems in British Columbia (BC)

In 2016, the BC Ministry of Health partnered with the Applied Science Technologists and Technicians of BC (ASTTBC) to develop “The Manual of Composting Toilets and Greywater Practice,” (The Manual) [120]. The ASTTBC is a regulatory organization that provides professional certification to technologists and technicians. The Manual is a technical document intended for use by Authorized Persons or those professionals that have been certified by the ASTTBC and are responsible for sewerage system design, construction, and maintenance. The Manual is consistent with the BC Sewerage System Standard Practice Manual, a reference manual for BC wastewater practitioners who plan, install, and maintain onsite sewerage systems. The Manual aligns with the Sewerage System Regulation, Environmental Management Act, Municipal Wastewater Regulation, and BC Building Code [120] (Figure 4-1). The Manual formalizes composting toilets as an onsite sanitation system option thereby enabling the implementation of sanitation systems that support the ecologically sustainable use of natural resources.

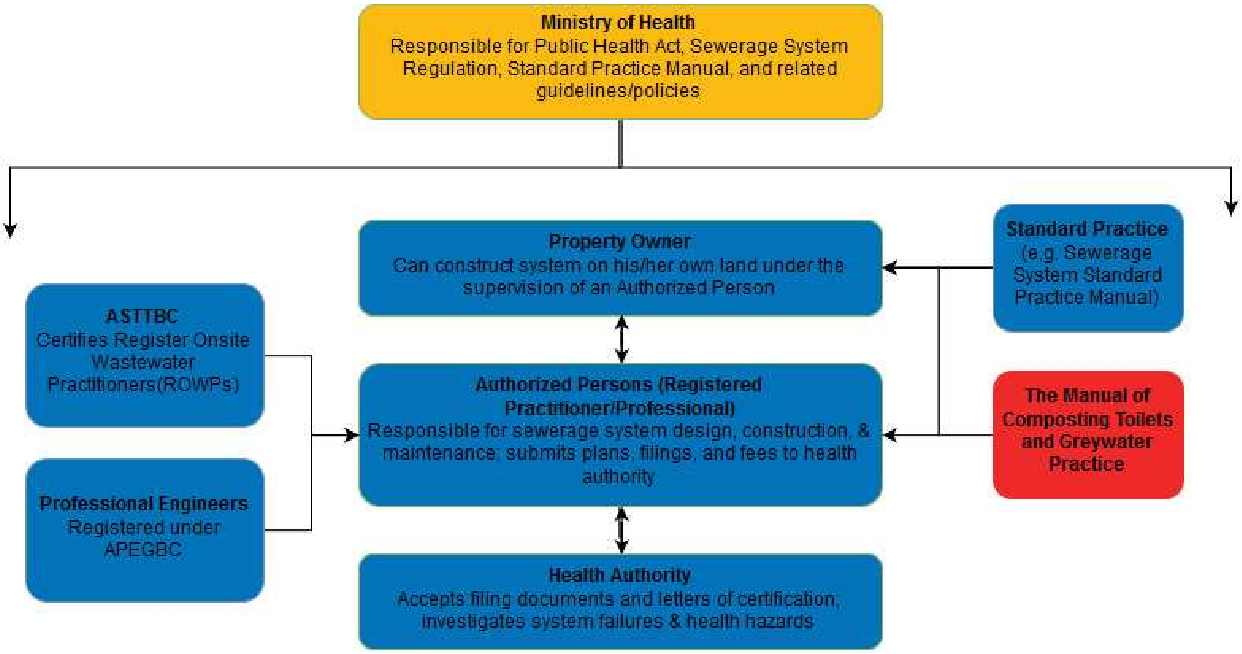


Figure 4-1 High-level summary chart of the stakeholders and organizations involved in the Sewerage System Administration Process. The Manual serves as a corollary to the “Standard Practice” and is embedded in the same processes used to install other sanitation systems like septic tanks.

The Manual bases its standards on a “multi-barrier approach” to risk management. In this context, a barrier is an element of the sanitation system that reduces the risk of human exposure to pathogens in excreta. A multi-barrier approach is the design of a sanitation system with multiple and intentionally redundant barriers to effectively manage and mitigate the potential risks.

Two key barriers described in the Manual are 1) how is the excreta treated, and 2) what are the disposal options for the end-product. The excreta treatment mechanism depends on the composting toilet design; common treatment mechanisms are high temperature, high pH, dehydration, and solar radiation. There are then three options for disposal::

- On-site surface discharge refers to surface discharge (including incorporation to the surface soil) of residual organic matter following the best practice guidelines of the Manual.
- On-site burial is subsurface discharge of residual organic matter by burial following the standards of the Manual.
- Off-site discharge is the transport of residual organic matter to a sanitary landfill or approved composting facility.

The Manual details the requirements necessary for each type of discharge. On-site surface discharge requires the most stringent testing, including analysis of metal levels and homogeneity, and off-site surface discharge requires the least. The AP designs the barriers and choice of discharge as components of the overall system design and maintenance plan that are informed by site and soil evaluations.

Composting toilets are not currently a defined option within the BC Building Code, but the Manual describes how a composting toilet can be presented as an alternative solution that a building official may accept as an equivalent to a water closet. Additionally, accessory buildings (e.g. garden sheds, detached garages, structures to house composting toilets) that are less than 10 square meters do not require a building permit i.e. composting toilets may be installed in accessory buildings without consultation with a building official. Regulations are important for supporting and motivating technological innovation that supports sustainable development [121], [122].

4.5. Dissemination and implementation of a composting toilet system for UVic

The specific objective of the composting toilet project is to provide sanitation services to the UVic Campus Community Garden (CCG), demonstrate the BC regulations for composting toilet design and operation, and support research activities concerned with different aspects of innovative sanitation system design. The more general objective is to promote the dissemination and implementation of composting toilets as an evidence-based practice with improved sustainability performance compared to other sanitation systems.

For clarity, the roles of the various stakeholders involved in the project at UVic are described below:

- **CCG**: The CCG is a student group funded by students and managed by a volunteer board. The role of CCG in this project is the end-user of the composting toilet.
- **OCPS**: The OCPS is responsible for providing recommendations on the physical development of the campus as it connects to long-term sustainability. The role of OCPS in this project is to facilitate coordination between different on-campus actors.
- **Department of Facilities Management (Facilities Management)**: Facilities Management is responsible for the stewardship of the university's lands and buildings including the development of new buildings. The role of Facilities Management in this project is to ensure that all infrastructure related to the project adheres to both UVic and provincial standards.
- **PH2E**: The PH2E Lab is a research group in the UVic Civil Engineering department focused on access to water and sanitation in low-resource contexts. The role of the PH2E lab in this project is to manage the project; this principally involves coordinating the different stakeholders and fundraising.
- **Registered Onsite Wastewater Practitioners (ROWPs)**: Ian Ralston and Ed Hoeppner are both certified ROWPs and co-editors of the Manual. The role of the ROWPs in this project is to confirm that that the composting toilet system is built according to the standards in the Manual.

4.5.1. Exploration

In the Exploration phase, various stakeholders come together to identify the appropriateness of a evidence-based practice [110]. The Exploration phase of the UVic composting toilet project was collaborative and consisted of multiple actors cross-campus. An initial connection was made between the CCG, the PH2E Lab in the UVic Civil Engineering (CIVE) department, and OCPS The UVic CCG was interested in installing an ecological sanitation system that contributes towards its objectives of stewardship, community building, sustainable food production practices, and education; the PH2E Lab has and will continue to engage in sustainable sanitation research; and one of the roles of the OCPS is to facilitate projects that contribute to the campus' overall sustainability objectives.

In addition to cross-campus actors, Vancouver Island ecological infrastructure advocates and practitioners including EcoSense, OUR Ecovillage, and the Polis Project on Ecological Governance provided input to initial data gathering and applications for fundraising.

4.5.2. Adoption/Preparation

The principal activities of the Adoption/Preparation phase were 1) designing a toilet structure and composting and toilet system acceptable to all stakeholders and 2) fundraising to build both toilet structure and composting toilet system. Through these two activities, this phase developed institutional-level comfort with and understanding of both the technical and regulatory aspects of composting toilet systems as well as how such projects are implemented on the UVic campus.

4.5.2.1. Structure and system design

The PH2E Lab, CCG Board, and the ROWPs collaborated on the design of the toilet structure and system (see Supplementary Information 3 for complete architectural drawings). The toilet will serve 90 plot renters at the CCG and approximately 20 weekly volunteers. The building is designed for an intended 10-year lifetime. Operation of the toilet involves the use of a carbon cover material (e.g. sawdust) to "flush" after using the toilet. Both the cover material and urine diversion function to suppress odors and manage moisture. Cover material that has a higher carbon content, small particle size, and higher rate of decomposition is advantageous. The design is aligned with current regulations as well as both scientific and practitioner consensus. The technical design of the toilet is urine-diversion with a moldering (i.e. slow composting) batch system (Figure 4-3).

The advantages of this system are the simplicity of management and its low cost. The primary disadvantage of this system is the relative complexity (when compared to flush toilets and other designs of composting toilets) arising from the separate management of urine, leachate, and excreta.

The urine management system consists of a preliminary phase of urine storage and then subsequent subsurface irrigation using mulch basins. During storage in a sealed container, urine is sanitized due to the natural conversion of the urea in urine to NH_3 [123]. The conversion of NH_3 increases the pH, which further drives the reaction of urea to NH_3. Both an increased pH and increased concentrations of NH_3 contribute to the inactivation of microorganisms.

The excreta management system consists of decomposition in a closed moldering bin. Leachate can drain out from the bottom of the moldering bin and is managed with the same system as the urine. Greywater (e.g. from the handwashing basin) is managed with a similar mulch basin system. The excreta and cover material reach a stabilized state after a period of 12-18 months at non-thermophilic temperatures [124]. Prior to land application, the decomposed material is tested for *E. coli* content per the requirements of the Manual [120].

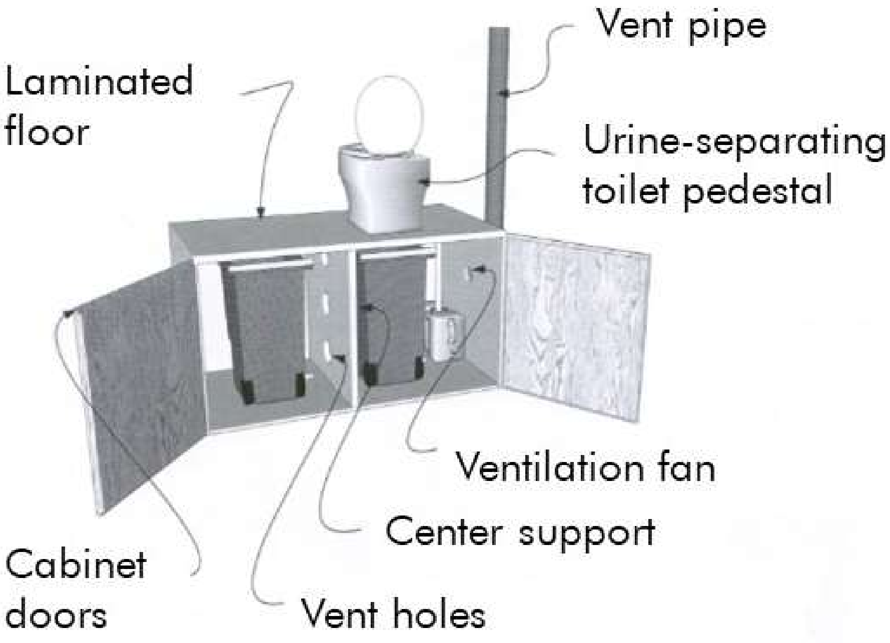


Figure 4-2 The design of the toilet is a moldering toilet with vented cabinet (drawing modified from [124]). The cabinet is vented with a solar-powered fan. The urine-diversion seat is a Separett Privy 500.

4.5.2.2. Fundraising

The total project budget is $24,000 (Figure 4-4). Over 90% of the funding is from UVic sources; the UVic Campus Sustainability Fund is contributing $15,000 to the project. The Campus Sustainability Fund is an on-campus initiative to promote projects that align with the university's sustainability action plan with preference given to projects that support student learning opportunities [125]. The Civil Engineering department, PH2E Lab, and the Student Sustainability Movement are also providing financial support to the project. The remaining funds are in-kind contributions from the ROWPs and Facilities Management to cover a portion of the labor costs associated with the project. The CCG is financially responsible for ongoing maintenance and operating costs.

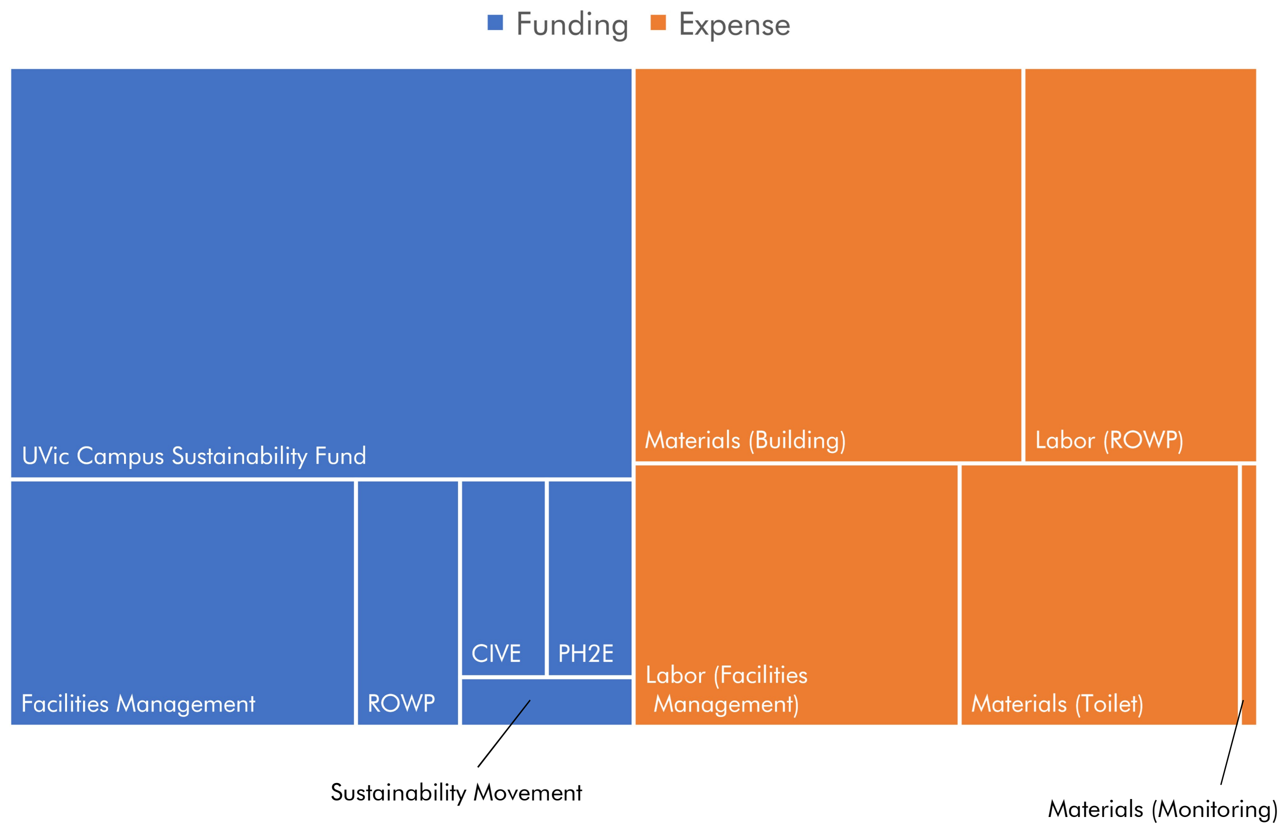


Figure 4-3 Budget summary for the design and installation of the CCG composting toilet.

4.5.3. Implementation

Implementation is based on the planned implementation supports from the Adoption/Preparation phase: Facilities Management will build the toilet structure based on the design drawings and the ROWPs will install the toilet system as described.

4.5.4. Sustainment

Sustainment of an evidence-based practice like composting toilets requires a continuation of processes and supports with allowance for adaptation [110]. The proposed activities to support the widespread implementation of composting toilets include formalizing the composting toilet at UVic as a training site, producing a document that clarifies the implementation process from the property owner’s perspective, and researching the advantages and feasibility of composting toilets. These activities will 1) transmit the lessons learned from the pilot project and 2) provide a space for research to improve both the implementation process and understanding of the technology. Overall, the objective of the sustainment phase is to ensure that there is continued used of the composting toilet on the UVic campus as well as an increased dissemination and implementation of composting toilets in BC.

A key stakeholder in the context of composting toilet dissemination are those professionals that are responsible for designing and maintaining composting toilet systems. The ASTTBC certifies professionals that install and maintain on-site sanitation systems, which now includes composting toilet systems. The ASTTBC wrote a letter of support endorsing the project and expressed interest in using the project long-term as a training facility for professionals interested in learning more about how to install and operate composting toilets. This Sustainment activity focuses on a critical aspect of the composting toilet installation processes.

In comparison, the Sustainment activity that clarifies the implementation process from the property owner's perspective is focused on the broader context: is lack of information a barrier to property owners' adoption of composting toilets?

A final Sustainment activity is research by various UVic groups to evaluate the technology with the objective of either iteratively improving the technology itself or investigating the advantages of composting toilet systems. This research has the potential to promote adaptation e.g. by improving the usability of the technology or by providing a basis for incentivizing the use of the technology. An example of this type of research is a study that evaluated how composting toilets are more cost-effective at mitigating nitrogen pollution relative to other sanitation systems; in follow-up to this research, residents are now offered a $5,000 incentive to install a composting toilet [36]. The following research project have been proposed:

- Measuring ventilation rates and temperature within the composting toilet sanitation system to determine whether there is enough energy to achieve in situ pathogen inactivation (per the findings in Chapter 3);
- Characterising the functional microbial ecology of composting toilet sanitation systems;
- Development of field-friendly tools to support monitoring and operation of composting toilet sanitation systems;
- Monitoring the greenhouse gas emissions from composting toilet sanitation systems; and
- Evaluating the occurrence and fate of emerging contaminants in composting toilet sanitation systems and resources recovered from them.

A key determinant of success in the Sustainment phase is the rate of dissemination and implementation of composting toilets in BC.

4.6. Factors influencing the dissemination and implementation of a composting toilet system for UVic

Here we identify the following as factors that facilitated the implementation of a composting toilet system in the Exploration and Adoption/Preparation phases: research and outcomes that support the evidence-based practice (including supporting policy and regulation), beneficial features of the evidence-based practice, and the individual characteristics of UVic and the CCG as adopters. We also identified factors related to the limitation of the evidence-based practice as well as characteristics of UVic as an adopter that hampered the progress of implementation.

4.6.1. Research and outcomes supporting the evidence-based practice

There is significant research and outcomes confirming the advantages of composting toilets. The most significant outcome supporting composting toilets is its integration into BC's Sewerage System Standard Practice Manual. The Manual provides performance-based standards (rather than being prescriptive), which provides opportunity for innovation. It also clarifies the context for implementation and serves as a resource for adopters.

There is an enabling regulatory environment for composting toilets in BC In 2016, the BC Ministry of Health established composting toilets as equivalent to toilets connected to septic tanks [120]. This is comparable to the regulatory environment in Oregon where composting toilets have been an option in the state residential plumbing code since 1978 [126]. Both BC and Oregon have less an enabling regulatory environment than Falmouth, Massachusetts. In Falmouth, the cost of retrofitting a septic tank system to a composting toilet in was $5,435 in 2014 [126]. In response to a study that showed the potential of composting toilets to improve nitrogen mitigation, residents were able to access a $5,000 incentive [36].

Largely, there is coherence between the Manual and the existing regulatory environment. However, there is still one identified gap that exists between the BC Building Code and the Manual. The BC Building Code does not recognize composting toilets as a defined option, but can instead be proposed as "alternative options" that may be approved on a case-by-case basis by the local building official [120]. This introduces an element of uncertainty that could perhaps impede dissemination and implementation of composting toilets.

4.6.2. Individual adopter characteristics

Both the CCG and UVic were good "fits" for the composting toilet project in how both the features and operation of the toilet connect to the organizations' broader missions and objectives around sustainability. The implementation of a composting toilet aligns with the CCG's objectives of stewardship, community building, sustainable food production practices, and education. By installing a composting toilet with separate urine collection, the CCG would be able to:

- Steward: Minimize water use and practice "water-wise practices" as stipulated in the CCG's use agreement (University of Victoria Office of Campus Planning and Sustainability, 2017).
- Build community: Collaborate with the UVic Civil Engineering department and the OCPS to increase the "awareness of local and global sustainability issues within the campus population and the surrounding community" per the Sustainability Action Plan
- Participate in sustainable food production practices: Produce a soil amendment that can be used to enrich topsoil and improve soil fertility.
- Educate: Serve as a testbed for an innovative water use reduction practice that can be replicated elsewhere on campus; and per the UVic Campus Plan, provide a living laboratory, where "opportunities for study, research, observation, or interpretation" are integrated into an outdoor space and allows for UVic to "showcase leadership in sustainability," (University of Victoria Office of Campus Planning and Sustainability, 2016).

Similarly, the implementation of a composting toilet aligns with UVic's Sustainability Action Plan for Campus Operations in two principal ways: "to be an innovator in water use, recovery, reuse, and stewardship" as well as to "work with campus partners to increase the awareness of local and global sustainability issues within the campus population and the surrounding community." Through this project, UVic identified a unique opportunity to apply and demonstrate the principles of the Manual regionally, thereby serving as a both an educator and innovator in water use and stewardship.

Despite the appropriateness of fit for the technology, there was a lack of clarity and consensus amongst stakeholders regarding the mechanics of implementation. The lack of clarity and consensus can be attributed to the stakeholders' concerns around risk for construction and responsibility (including financial) for ongoing operation and maintenance of the structure and system. These concerns resulted in a drawn-out Adoption/Preparation phase because they were not considered in the Exploration phase. Once these concerns were identified, it was possible to clarify roles and responsibilities and identify a mutually agreed upon implementation strategy.

4.6.3. Factors that relate to the evidence-practice itself

The beneficial features of composting toilets are represented by its integration into the BC Sewerage System Standard Practice Manual and were recognized by both CCG and UVic as adopters. The recognition of the beneficial features is also reflected in the diversity of funding sources, letters of support, and input provided to the project.

However, a key limitation of composting toilets is reflected in the scheme of responsibilities compared to sewered sanitation systems. This is one of the factors that impeded consensus amongst stakeholders. In sewered sanitation systems, the user of the system has limited responsibility for the operation and maintenance of the system with regards to the treatment and disposal of excreta. Instead, the burden of responsibilities is managed by operators at wastewater treatment plants. In comparison, the user of composting toilet systems is significantly implicated in the steps of treating and disposing of excreta. It requires ongoing monitoring and maintenance (and in BC an ongoing engagement with a ROWP) to ensure the system is performing to standards. This shift in responsibilities is significant and requires long-term commitment (both financial and operational). Once identified as a factor that impeded consensus, documents detailing long-term roles and responsibilities as well as budgeting were drawn up and agreed-upon by the stakeholders. Given that the toilet will be publicly accessibly, liability was a concern that was resolved in this discussion concerning responsibilities as well.

A secondary limitation (less applicable in this case given the pilot nature of the project) concerns the cost of the toilet. Considering only those costs associated with the toilet system (i.e. omitting the material and labor costs for building the structure around the toilet), the costs for materials sum to about $4,500 and the costs for contracting a ROWP sum to about $5,500. It is possible that innovation could lead to cheaper material costs and that ROWP costs will decrease as these systems become more universally accepted and more ROWPs are trained on these systems. In the short-term, cost could be a barrier to adoption.

4.7. Discussion

Sustainable development refers to meeting the needs of the present without compromising the ability of future generations to do so [1]. Composting toilets are a sustainable sanitation system. The short-term applications of composting toilets include:

- Retrofitting pit toilets like those used in BC provincial parks;
- Replacing the long-term usage of portable toilet rentals;
- Meeting household on-site sanitation needs (e.g. households in rural areas or in the Gulf Islands that currently use a septic tank system); and
- Diversifying portable toilet rental options in short-term usage cases like at festivals and other events.

Promoting the widespread dissemination and implementation of composting toilets (in the use cases identified and otherwise) requires an improved understanding of those processes and factors that facilitate – or impede – systematic uptake. Evaluating the Exploration and Adoption/Preparation phases of the project to install a composting toilet at UVic identified the following facilitative factors: supportive and self-reinforcing research and outcomes, favorable adopter characteristics, and the technology’s beneficial features.

In addition to using this project to facilitate widespread dissemination and implementation of composting toilets in BC, there is a special opportunity to use the project to educate and inform future generations of civil engineers of truly sustainable sanitation systems beyond the “porcelain dream”. It is recognized that most universities focus on teaching conventional techniques and systems without creating space for discussing innovative and alternative options [127]. The development and implementation of new sustainable technology is highly uncertain and characterized by risk: technical, market-related, organizational, and institutional [128]. Pilot projects can be used to manage those risks by providing a critical space for learning-by-doing, create actor networks that shape technological development, and reinforce institutional and policy support. These three advantages are highly visible in the case of the CCG composting toilet project and provide insight into how to shift the current sanitation paradigm towards improved sustainability.

4.8. Supplementary Information 3

5. Discussion

This thesis is founded on the two-part question: what is wrong about the current global sanitation paradigm, and what can we do better? The first manuscript examines the implications of sanitation infrastructure accessibility and choice on the functioning of the nitrogen cycle, a key planetary system. The second manuscript is a preliminary foray into the feasibility of drying as a treatment mechanism. The third manuscript interrogates the readiness of the regulatory environment, technology, and adopters for alternative sanitation systems. The hypothesis underlying these three manuscripts is that sanitation systems that are capable of 1) decentralized treatment, 2) entail source separation, and 3) integrate resource recovery have a greater capacity for sustainability than the Porcelain Dream (i.e. flush toilets, waterborne sewerage, and centralized wastewater treatment).

5.1. The Porcelain Dream views excreta as a problem rather than a resource

I have referred to the current global sanitation paradigm as a crisis. Most times when I say this, people assume that I am referring to the global inequity that is that "more people have access to a cell phone than a clean and safe toilet," [129]. Indeed, the United Nations Sustainable Development Goal (SDG) 6 is dedicated to water and sanitation, and the primary metric of success is to "achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations," [130]. This is an admirable metric: it reinforces the concept that sanitation is a fundamental human right and commands us to direct our efforts to marginalized sections of society [99]. However, the indicator used to measure this metric is "the availability of improved sanitation services," defined as those systems available at a household level that safely contain and treat excreta [130]. A principal limitation of this metric and indicator is that it implies that excreta is a problem to be managed rather than a resource to be harnessed. Based on this limitation is the subsequent assumption that the Porcelain Dream is **enough**.

Piped sewerage and centralized wastewater treatment plants are the sanitation system conventionally used in developed countries [43]. Initially, these systems were designed to minimize contact between the public and the pathogens found in excreta (and truly they are miraculous in how successful they are at this). Over time, the systems were iteratively improved to minimize impact to the surrounding environment by reducing nutrients loads of the water, but even effective systems discharge polluting nutrients to the air and to waterways [23], [26], [42], [50]. Other sustainability challenges faced by conventional systems include water use, greenhouse gas emissions, and micropollutant releases [43].

There has been an increased emphasis on addressing these sustainability challenges including resource recovery from wastewater [43]. Resource recovery can mitigate nutrient pollution from wastewater systems and has been framed as a solution to sludge disposal problems, but conventional wastewater systems are suboptimal for the recovery of nutrients because of the high dilution rate of the systems [43], [99], [131]. But even more centrally, these systems were designed to manage excreta as problem. What this means is that iterative improvements will never produce the paradigm shift required to fundamentally reframe sustainability challenges as opportunities.

To illustrate the shortcomings of the Porcelain Dream and demonstrate the opportunity for sanitation innovation to reframe a sustainability challenge as an opportunity, I explored the potential impact of widespread implementation of ecological sanitation on nitrogen in the global agriculture-sanitation system. I found that under the current sanitation paradigm a maximum of 23% of nitrogen in excreta is recovered and reused in agriculture with the remainder discharged to the environment with polluting impacts. In comparison, ecological sanitation has the potential to recover 86% of nitrogen in excreta (with the potential for technological innovation to improve this further). A primary difference between the current sanitation paradigm and ecological sanitation is whether excreta is viewed as waste or a resource. This is reflected in how the technology operates: ecological sanitation systems are designed to recover resources whereas resource recovery infrastructure has been added to conventional sanitation systems to manage nutrient pollution and sludge disposal problems. The objective of the nitrogen MFA was to demonstrate the effectiveness of ecological sanitation as an intervention to mitigate our disruption of the global nitrogen cycle as well as to challenge the assumption that the Porcelain Dream (with its paltry nitrogen recovery rate!) should be convention.

Other researchers have similarly promoted sustainable sanitation innovation by elaborating on the relationships between sanitation system design and planetary system functioning. Ryals et al. measured the greenhouse gas emissions from various waste treatment systems and identified that ecological sanitation systems can contribute to climate change mitigation [51]. Trimmer et al. more broadly developed a framework for the overlap between sanitation system functioning and ecosystem services (e.g. water quality, air quality); he and his colleagues thereby identified resource recovery's positive impact on ecosystem service functioning [132]. Both identified the interconnectedness of global health and ecological sustainability from the perspective that the two can be mutually self-supportive rather than competitive (i.e. you can have a toilet that protects your health and stewards the planet).

Another approach to promoting sustainable sanitation innovation is from the perspective of equity and access. An obvious example is the potential to harness the resources of excreta to achieve multiple SDGs like universal food security (SDG 2) and energy access (SDG 7) [22], [33], [132]. This perspective is mentioned briefly in my analysis of nitrogen material flows, but it is insufficiently analyzed to make a compelling contribution to the literature. A compelling future avenue research is comparing the geospatial distribution of nitrogen in excreta to the nitrogen in fertilizer i.e. could some regions achieve food security through sanitation? And more generally, the research omits a discussion regarding *how* this information might be used. Could sanitation be financed via nitrogen pollution mitigation offsets? What other information might a policymaker need to choose not to maintain the ageing infrastructure of the Porcelain Dream and invest in more innovative sanitation?

The principal implication of the nitrogen MFA is that from the perspective of nitrogen management, universal access to ecological sanitation is more sustainable than the conventional sanitation paradigm. This is important in both those contexts that already have access to improved sanitation services as well as those that do not. In many ways, we can see that there is a greater opportunity for innovative and sustainable sanitation design in resource-constrained contexts. Resource-constrained contexts do not have the advantage of available resources now and are thereby incented to design sanitation systems that are sustainable in the now and in the future. In comparison, developed country contexts that are not resource constrained (financially, water, energy, and otherwise) have married themselves to a sanitation system that is limited in its capacity to respond to sustainability challenges. It is imperative that we work towards, first, a universal acknowledgement of the dangerous imperfections of the current sanitation paradigm, and then, second, a widespread promotion of sustainable sanitation systems.

5.2. Are we ready for composting toilets?

Composting toilets are a sanitation system that respond to the sustainability challenges of the Porcelain Dream. The technology is an example of a "source separation and decentralization" (SSD) system. Source separation refers to the separate management of urine and faeces, and decentralization refers to the system being non-sewered. The advantage of source separation is that urine and excreta can be collected and treated appropriate to their specific requirements and overall management can be simplified [48], [133].

This has significant impacts on energy efficiency, greenhouse gas emissions, discharge of micropollutants to the environment, and the potential recovery of nutrients for reuse [134]. Similarly, decentralization offers efficiency benefits as the treatment systems are closer to the point of use thereby avoiding conveyance costs [135]. There is the potential for composting toilets to represent a "new normality" in the form of a sanitation system that operates both more ecologically and sustainably.

There is limited uptake of composting toilets despite their advantages. To explore why, I applied the EPIS framework to a composting toilet installation project on the UVic campus. The question behind the study is: how ready are the regulatory environment, technology, and adopters for this "new normality?" The high-level findings from this analysis suggested the likelihood of there being some adopters like UVic who are ready for composting toilets, but overall there is a need for outreach (specifically around demystifying the toilet installation process) and technology innovation that reduces the burden of operation on the system owner.

The obvious limitation of the EPIS analysis is that the project is incomplete and therefore all insights are in part contingent on the completion of the project. (How much can you learn from the preparation of a project that still has a possibility of failure?) A secondary limitation is the scope of the study: UVic has unique adopter characteristics and therefore the transferability of insights may be limited. A potential counter point to this limitation is that in many ways the adopter posed a high degree of barriers. Principally, the university is risk-adverse, and the proposed facility will be public. These two factors engendered significant concerns around liability, which impeded progress. In comparison, this project would have been simpler (both less expensive and quicker) to implement at a private household. Regardless, it would have been advantageous to compare this project to others done elsewhere and for other adopter types.

The principal implication of the findings is that there is both enthusiasm for and a hesitation about composting toilets. This is characteristic of the risks associated with early adoption. In many ways, composting toilets are an established technology, but from a regulatory perspective, composting toilets represent a new sustainable sanitation technology. The development and implementation of new sustainable technology is highly uncertain and characterized by risk: technical, market-related, organizational, and institutional [128]. Pilot projects can be used to manage those risks. Based on the findings of this analysis, it seems likely that many more projects – as well as innovation in technology as well as improved outreach – are required to accelerate adoption of this technology.

5.3. Is drying the basis of the technological innovation we need?

A principal shortcoming of many SSD systems is that the heavy operational burden falls on system users and owners. Compared to the Porcelain Dream, a composting toilet owner is significantly more involved with the maintenance of the sanitation system. My work to characterize fundamental drying characteristics of fresh faeces was motivated by the hypothesis that drying could be used as a treatment mechanism to reduce that burden. Drying can decrease mass and volume, inactivate pathogens, and serve as a critical step in resource recovery. [72], [76]–[79]. These all represent significant operational advantages in SSD systems where excreta are managed as a solid waste rather than a liquid waste.

Dried excreta that pose no public health risk could be managed in a way analogous to how North American cities manage household solid waste like garbage, recycling, and compostable kitchen scraps. The scalar value produced in the MSI study could be used to design a toilet that achieves enough in-situ pathogen inactivation with drying such that you could take your bin of excreta out to the curb in the same way you do your recycling. The nutrients in your excreta could be co-managed with the nutrients in your composting kitchen scraps [136].

There are still several unknowns that exist between the MSI study and this alternate reality. The principal one is that the study was performed with fresh faeces rather than faecal sludge when it is uncertain whether the material in an SSD system (like a composting toilet or other) behaves more like fresh faeces or faecal sludge, both of which are highly variable in their composition and other characteristics (and likely their drying characteristics as well) [34], [77].

To resolve some of these limitations, I am engaged in an ongoing research collaboration with the Pollution Research Group (PRG) at the University of KwaZulu-Natal in Durban, South Africa. The PRG is applying the same MSI method that we developed to varied faecal sludge sources so that we can compare the fundamental drying characteristics of fresh faeces and faecal sludge. Ideally, this characterization data could be used by technologists to innovate toilet design (as well as other faecal sludge management processes).

The MSI study was motivated by a lack of data regarding the fundamental drying characteristics of fresh faeces. The principal contribution of the MSI study is data that should be used to innovate SSD systems and thereby facilitate widespread adoption sustainable sanitation systems. The MSI study is the most granular and least applied of the three manuscripts in this thesis, but the key findings have the greatest potential for being integrated into technology and process design. An improved understanding of drying will facilitate the development of technology capable of decentralized treatment of excreta.

5.4. In summary

The question posed by this thesis is epic in scale, and the findings of my three manuscripts represent only a small contribution towards a potential answer. My objective was to communicate that the design of sustainable sanitation systems is an urgent issue that is both local and global in scale. There is work that needs to be done to innovate the technology available, promote an enabling environment, and challenge society regarding its assumptions around what is acceptable when it comes to the choice and accessibility of sanitation systems.

6. Reflections

Two years ago, when I was applying to UVic, I wrote:

> "I am applying to UVic's MASc in Civil Engineering program to contribute to Dr. Caetano Dorea's research project on [faecal sludge drying], expand upon the interdisciplinary research I've done with container-based sanitation to support SOIL in Haiti, and acquire engineering research skills to facilitate further work and research opportunities in international development…In the long-term, I want to be in a position to teach and continue to do impactful applied research."

In addition to accomplishing the above, I have also had the opportunity to teach, participate in international conferences, learn that I can do more to center equity in my research, and connect with practitioners and researchers operating in the sustainable sanitation space. My key takeaways are that academics need to be more emotionally present and implicated in our work, our research needs to respond to and anticipate the demands of policymakers, and seek out collaboration.

I am most grateful for the following experiences from my master's:

- Preparing content and delivering lectures in CIVE 444/580 Water and Sanitation for Developing Countries. I was challenged by and enjoyed learning how to deliver engaging lectures and facilitate participatory classroom discussions. I focused on teaching that 1) engineering in a developing country context is not a technological problem, and 2) from a sustainability perspective, water and sanitation are problems that remain unsolved in developed country contexts as well.
- Presenting research at and attending two international conferences: Water Engineering and Development Centre International Conference in Nakuru, Kenya and Water and Health in Chapel Hill, North Carolina, USA.
- Participating in the British Columbia Coalition Institute (BCCI) at UVic. The focus of the Institute was "Planetary Health," which is a field of research that illuminates the deep relationship and interconnections between human health and the health of the environment. I learned a lot from the facilitators and other participants. Notably, I learned that there is always more that I can do to center equity in my work and research.

This work and these experiences have laid the foundation for the long-term goal I expressed in my application. The first example of this is that I will be teaching CIVE 4444/580 in the spring of 2020 as a sessional instructor and will be using planetary health as a framework for the course. A second example is how I am now working with the lead author of the *Manual* to evaluate the feasibility of a composting toilet residuals composting facility on Hornby Island for the Comox Valley Regional District. In the longer-term, I anticipate pursuing PhD research in the space of urban services provision and ecological infrastructure.

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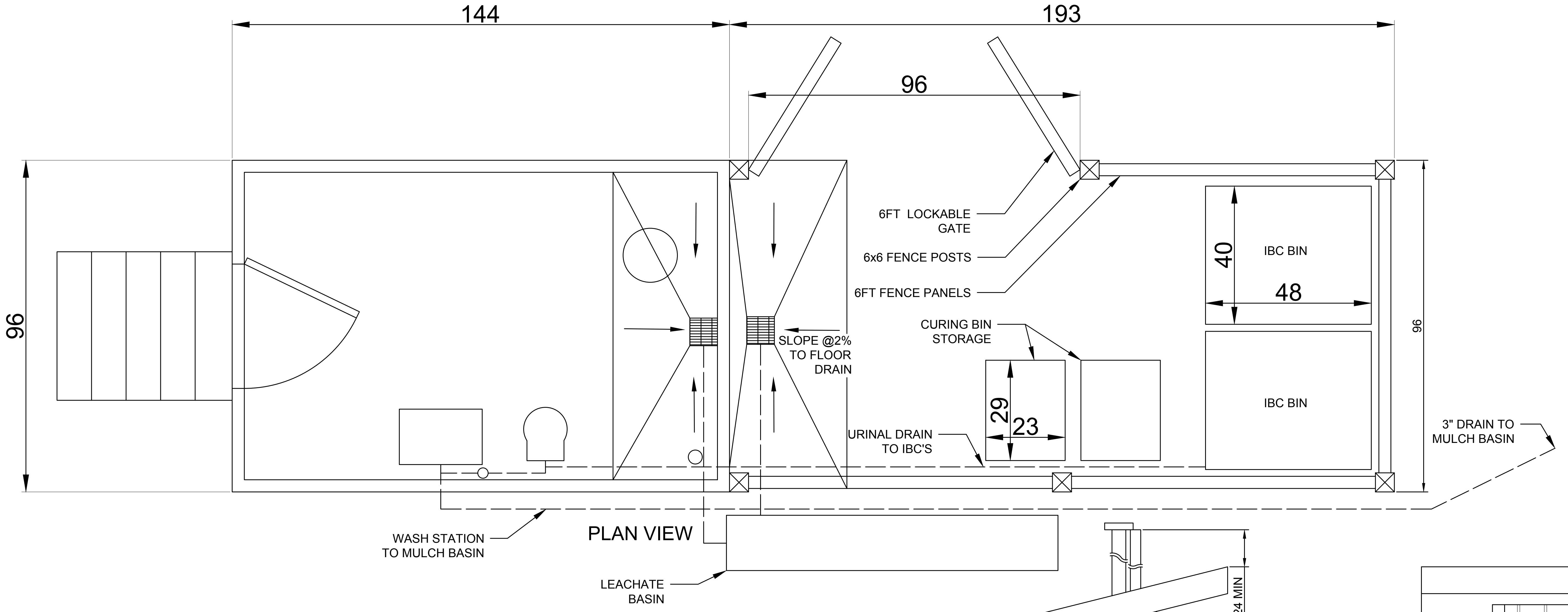

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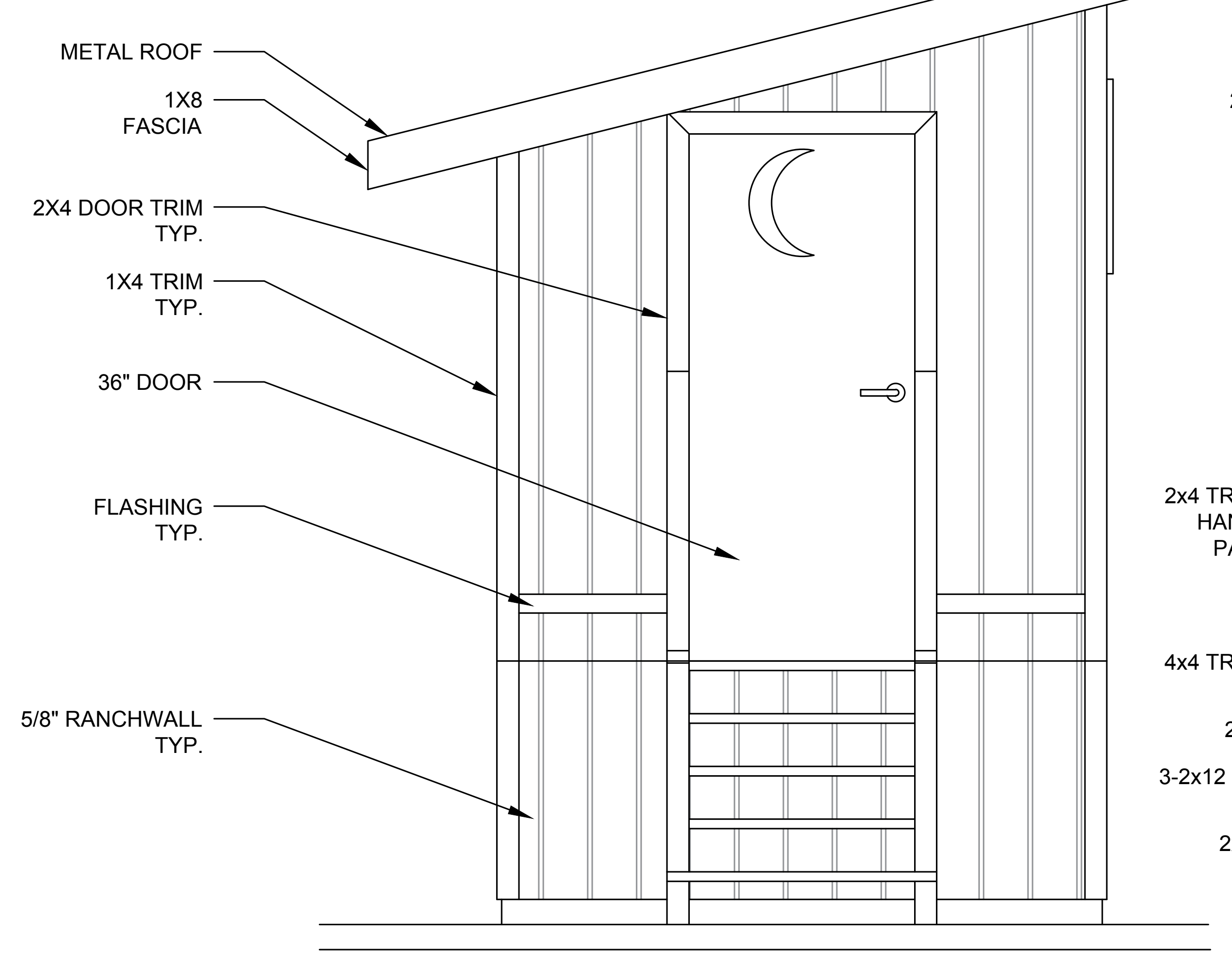

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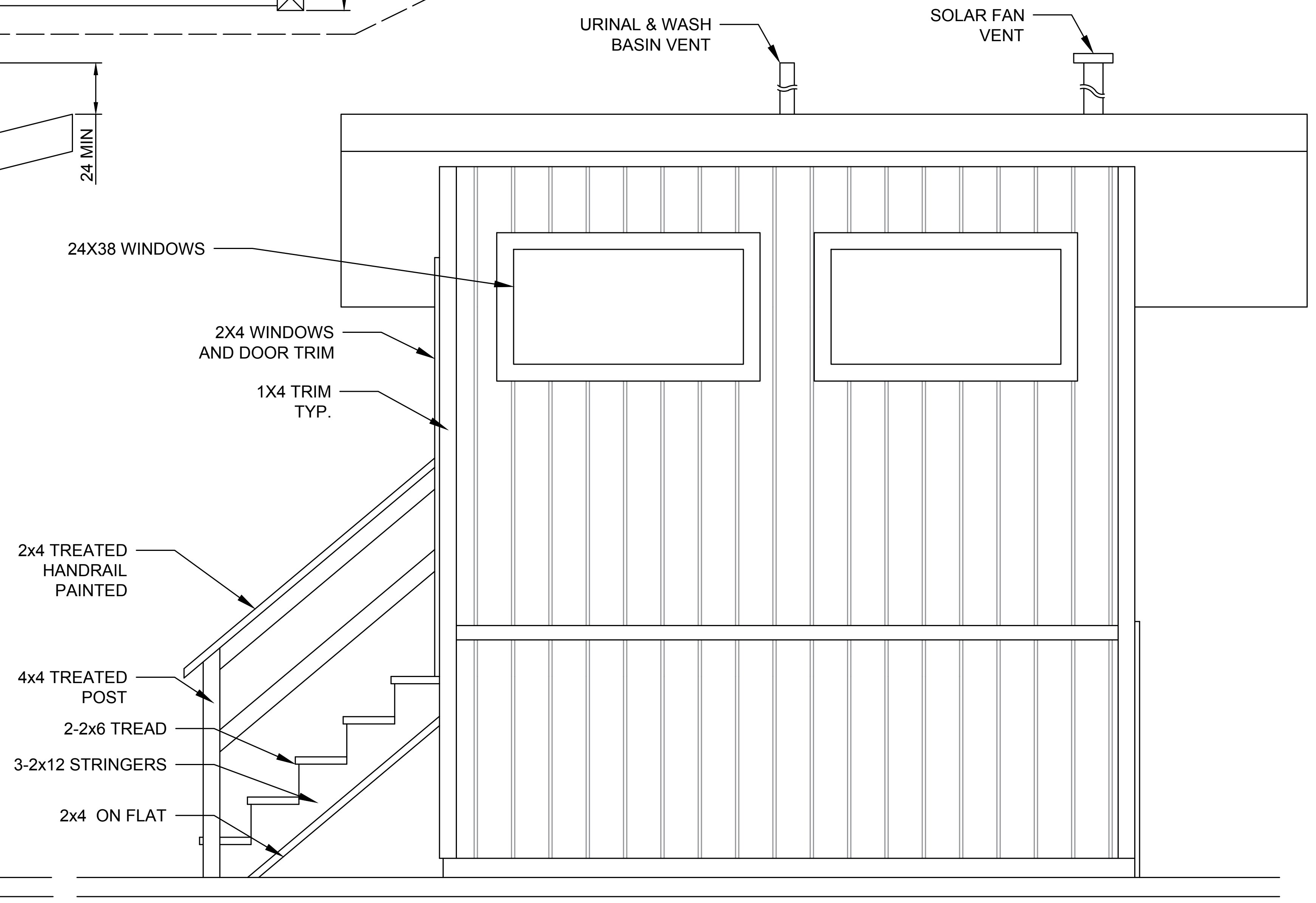

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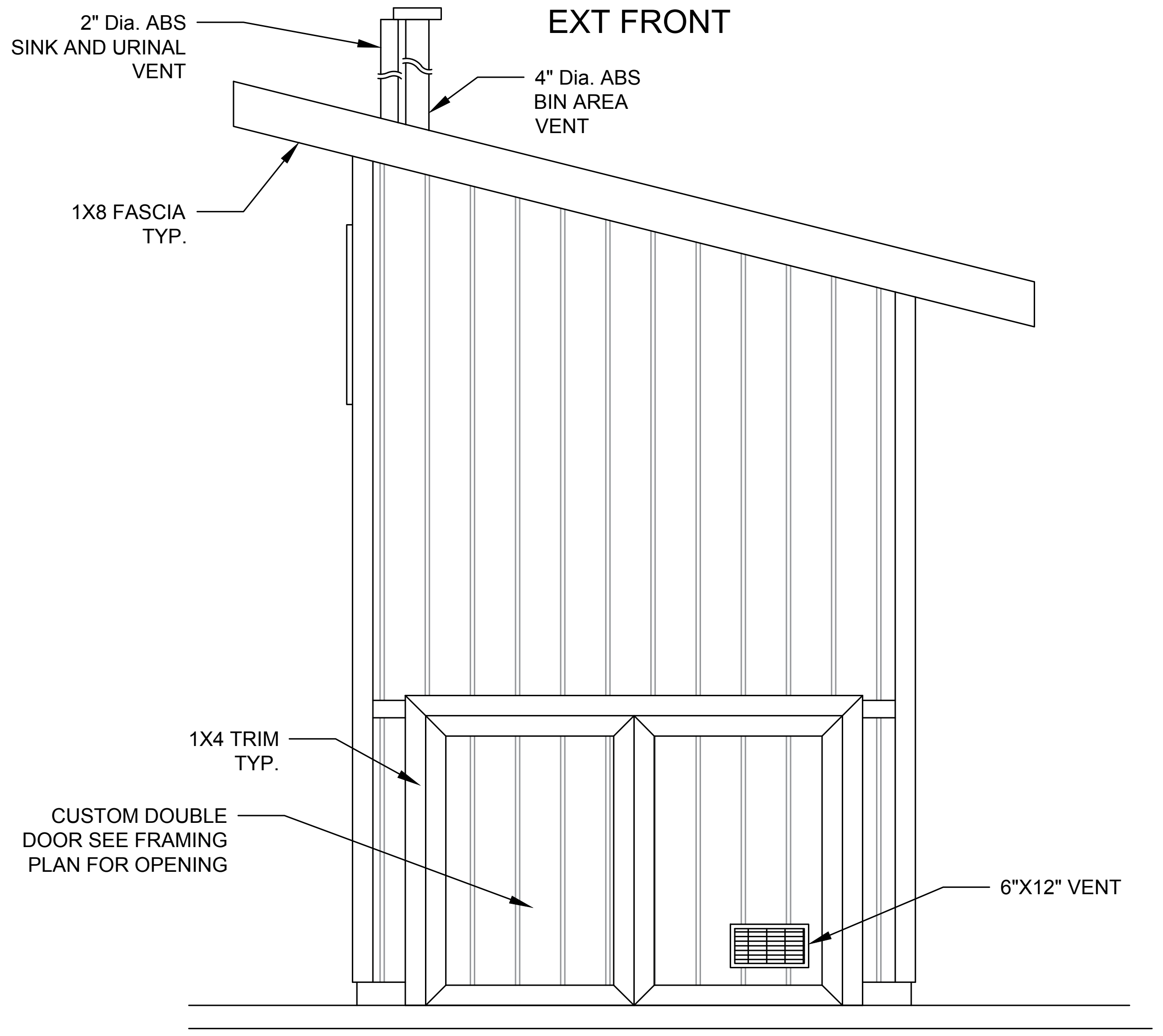

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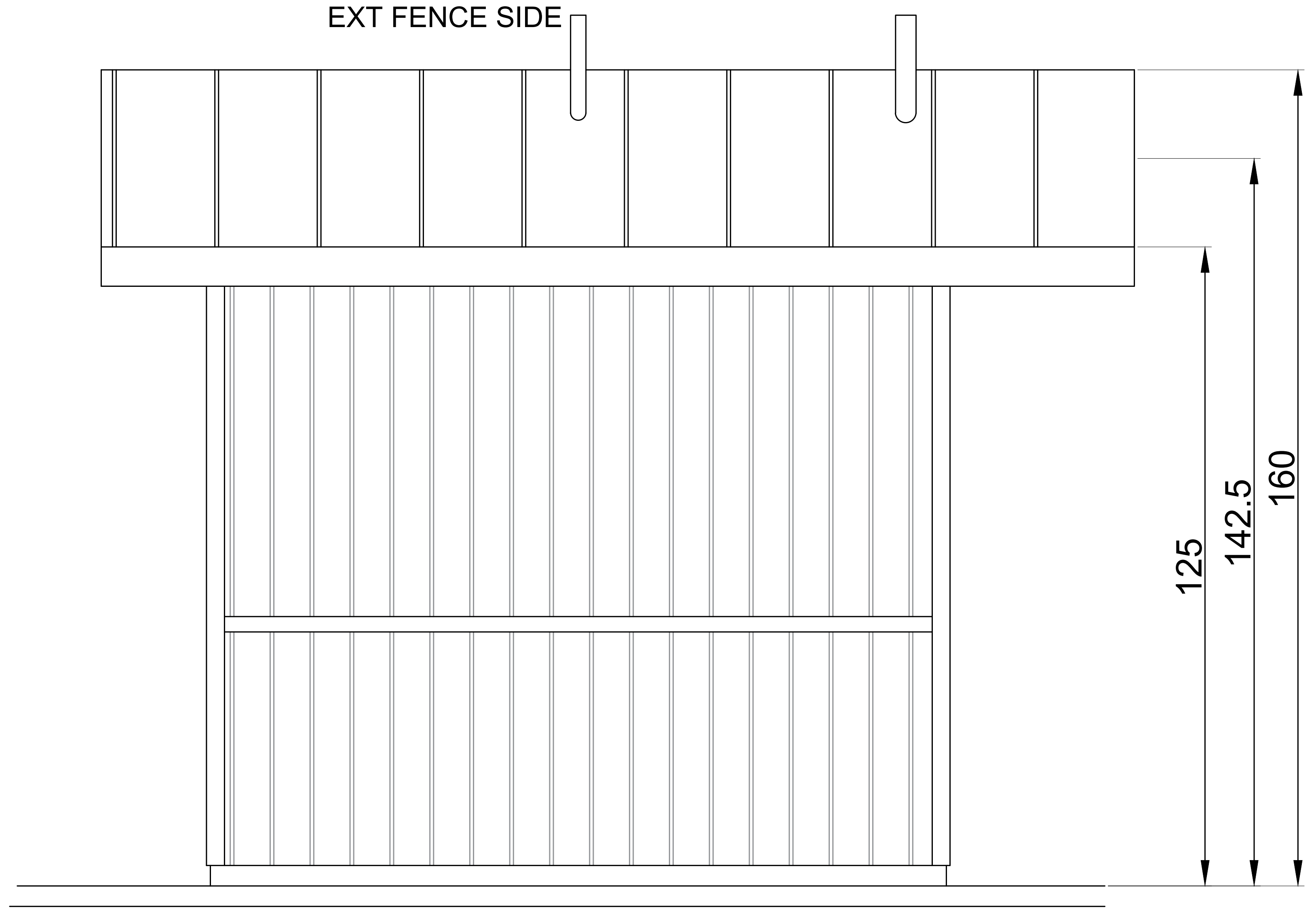

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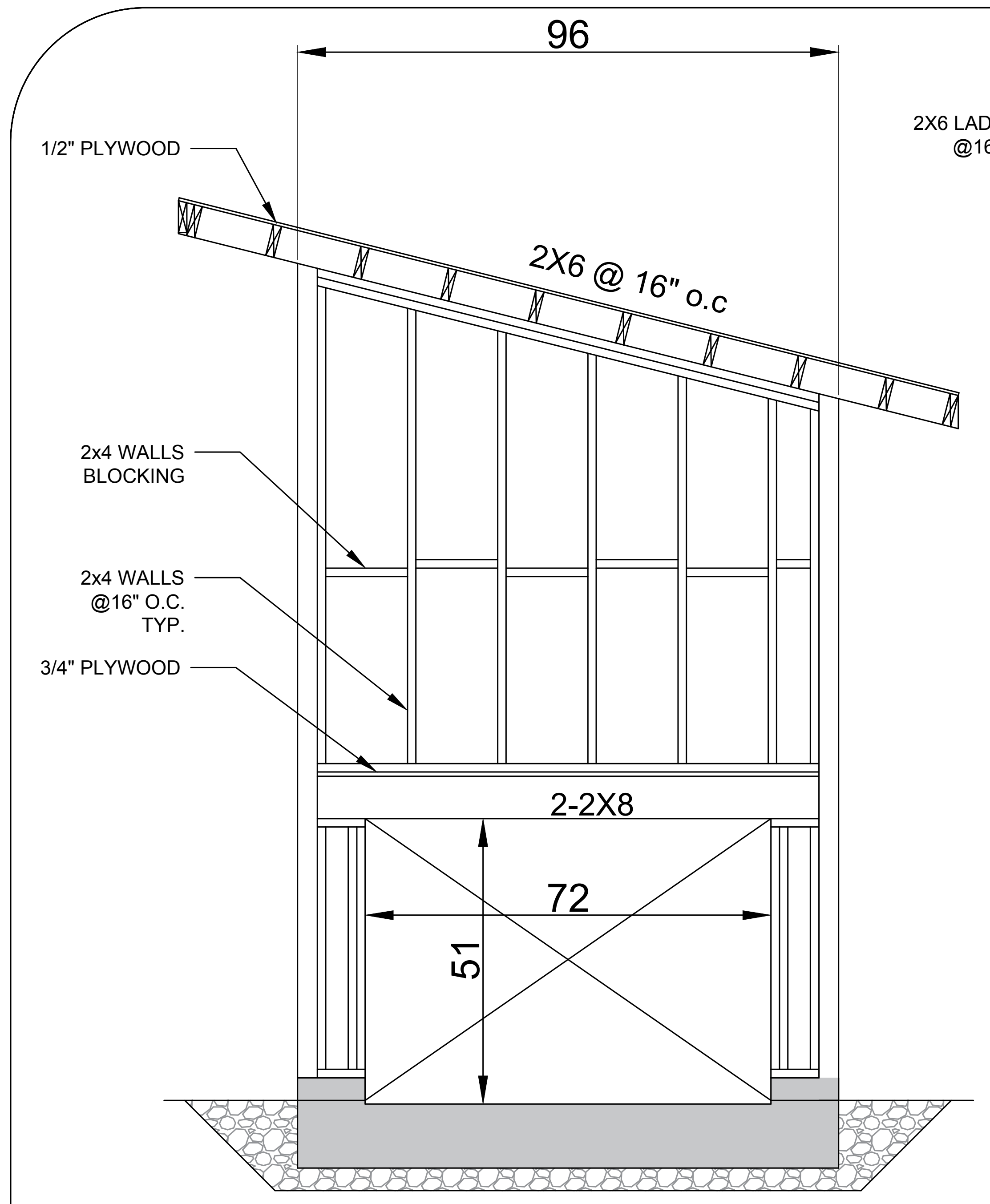
General Notes

No.	Revision/Issue	Date
4	ADDED CONC. CURB & SLOPE	16/08/19
2	ADDED SLOPE	24/07/19
1	ADDED 1X8 FASCIA BOARD	16/07/19

Firm Name and Address

Project Name and Address
COMPOSTING TOILET

Project
COMPOSTING TOILET
Date
7/11/2019
Scale
1:24
Sheet
A1



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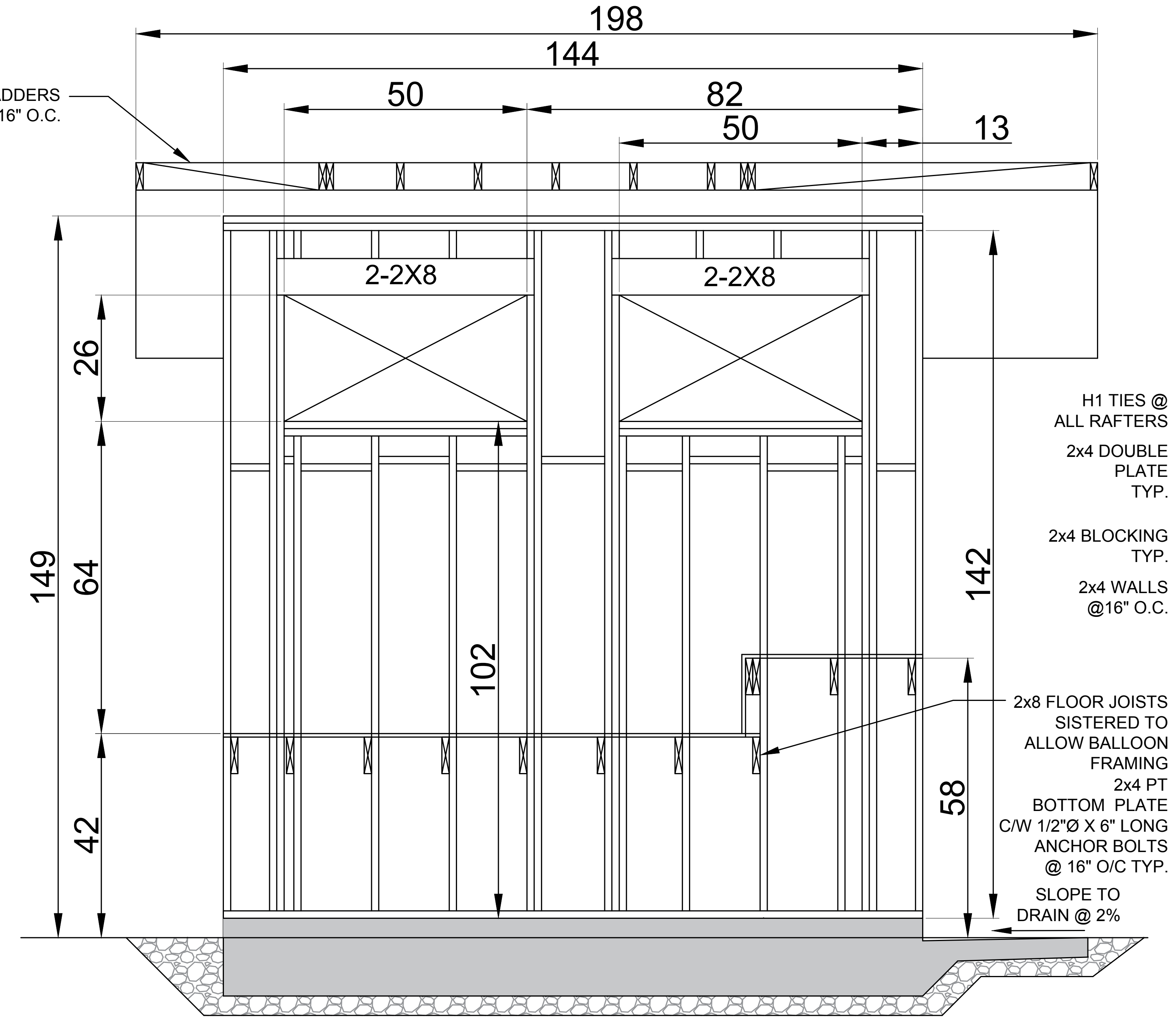

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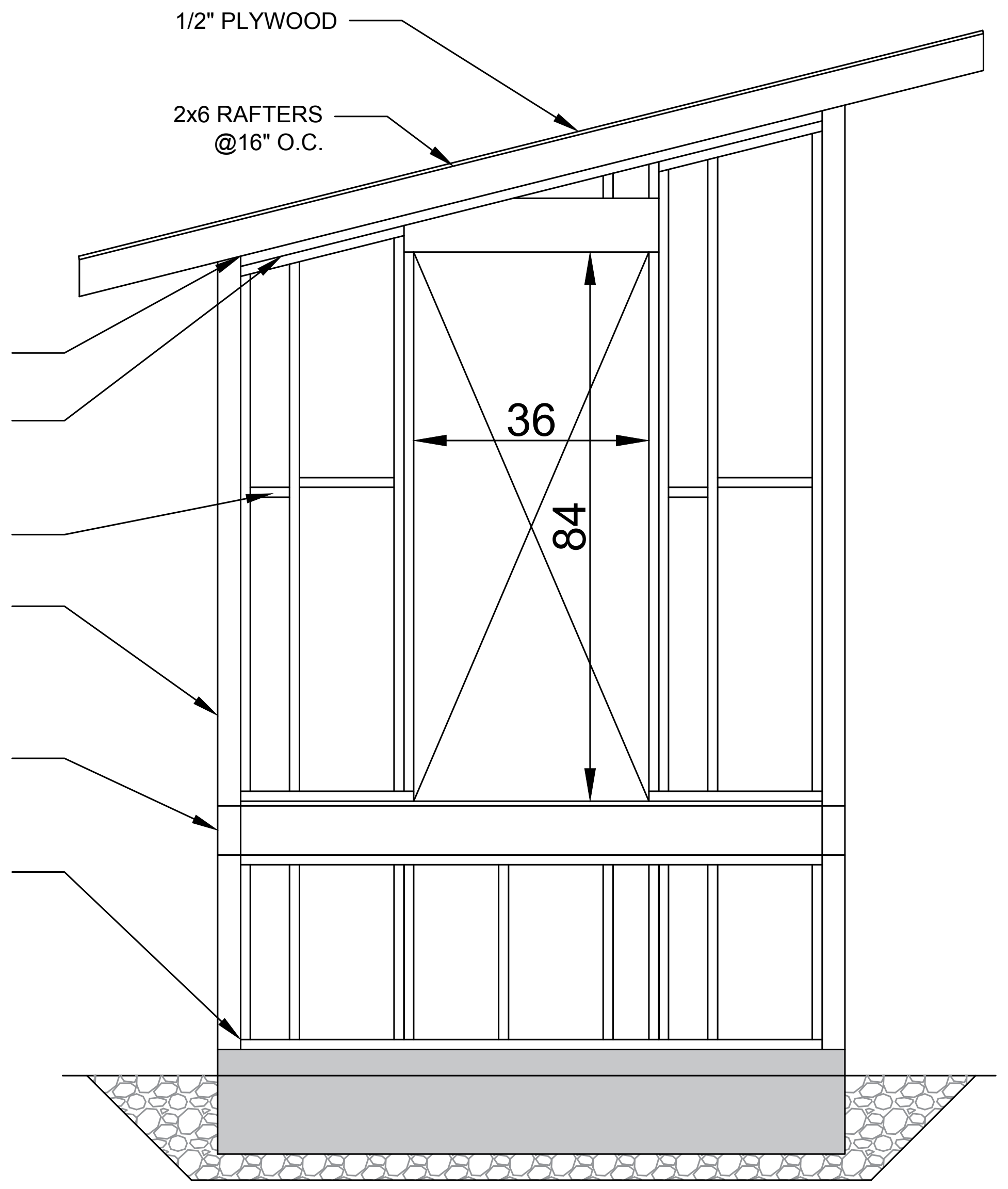

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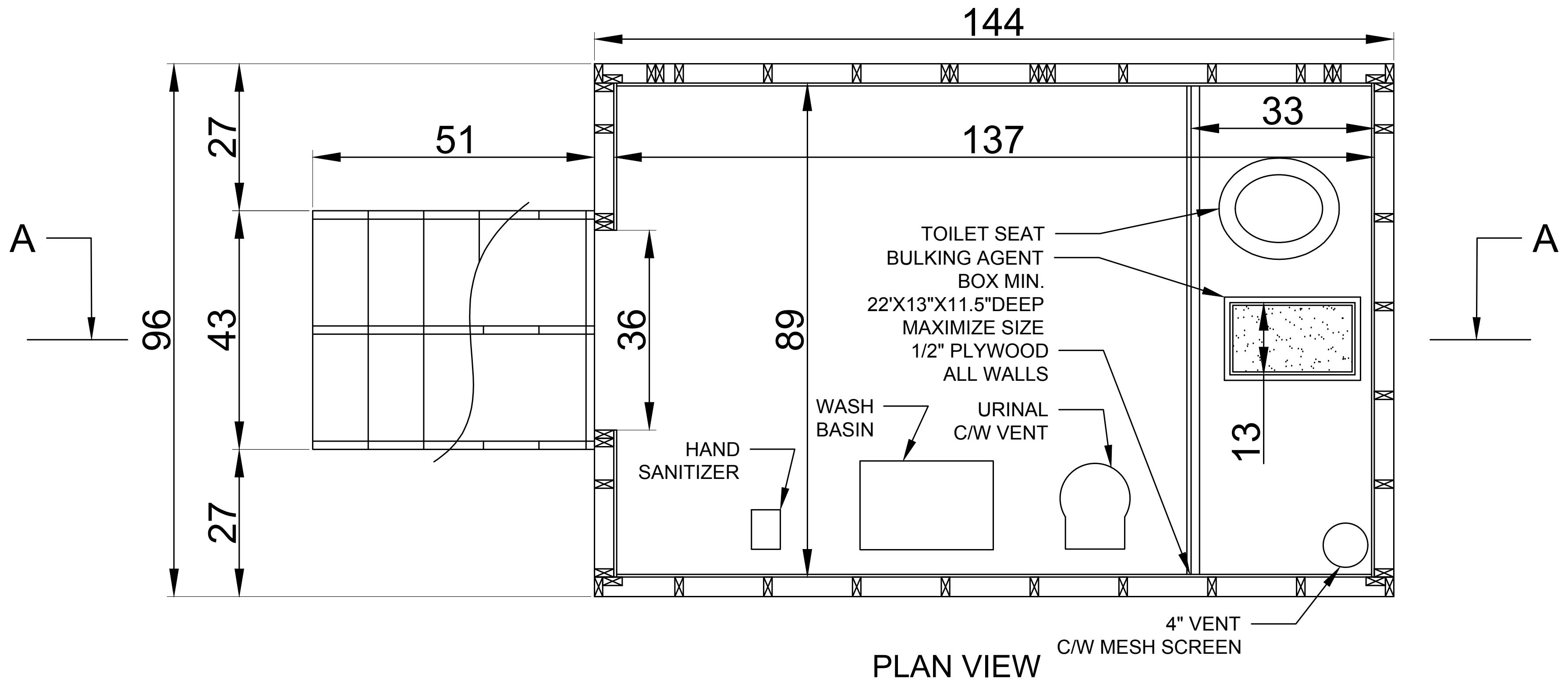
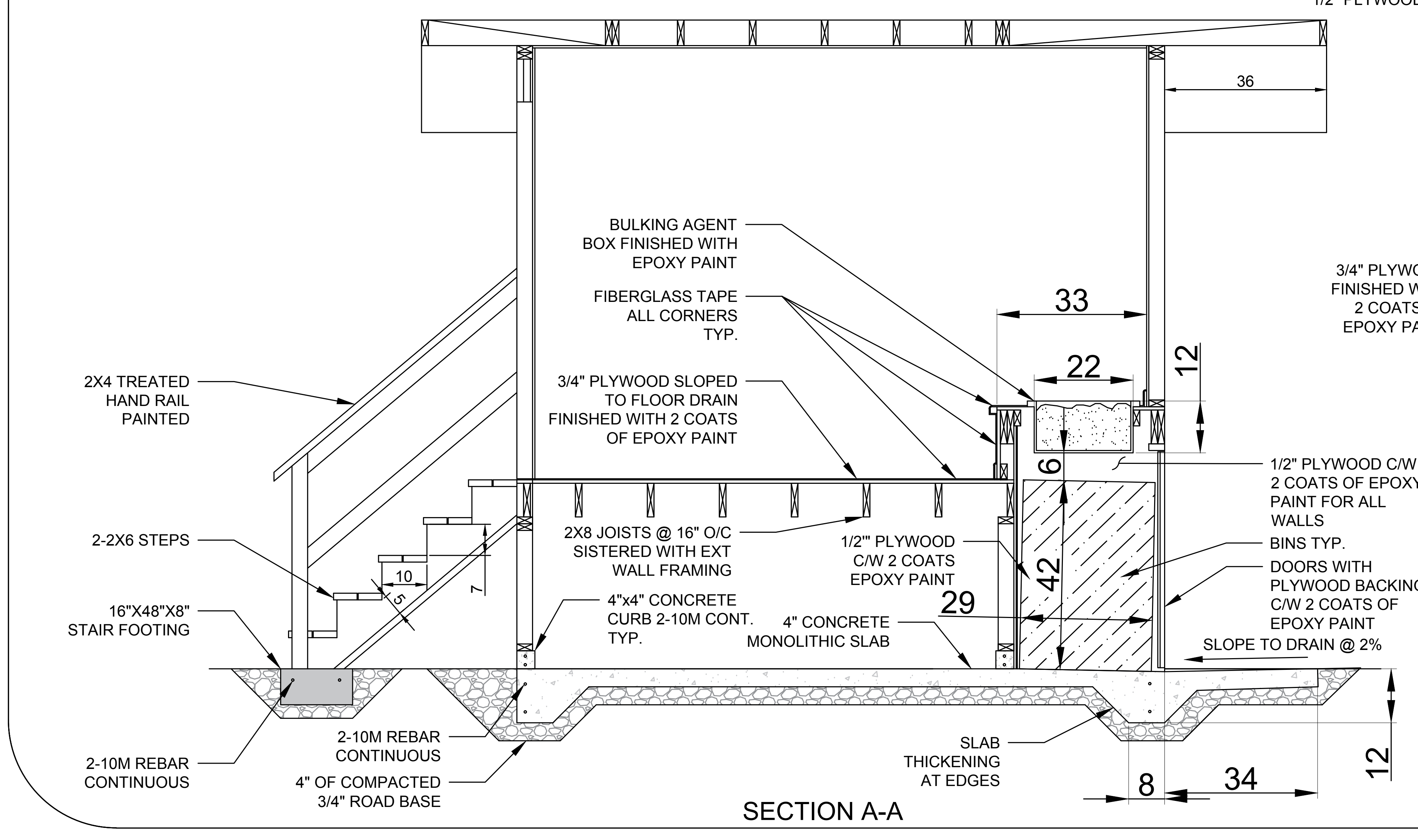


PLAN VIEW



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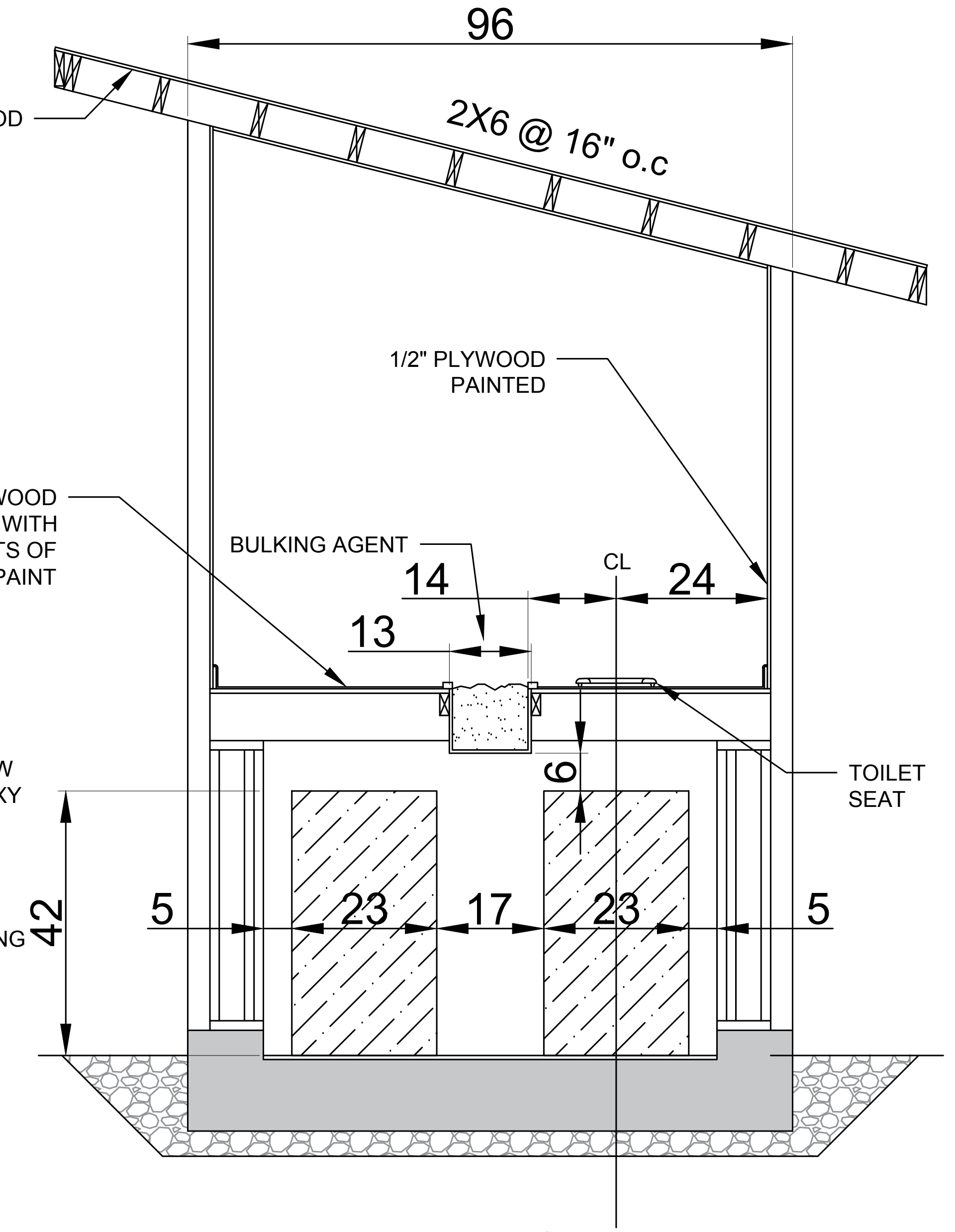

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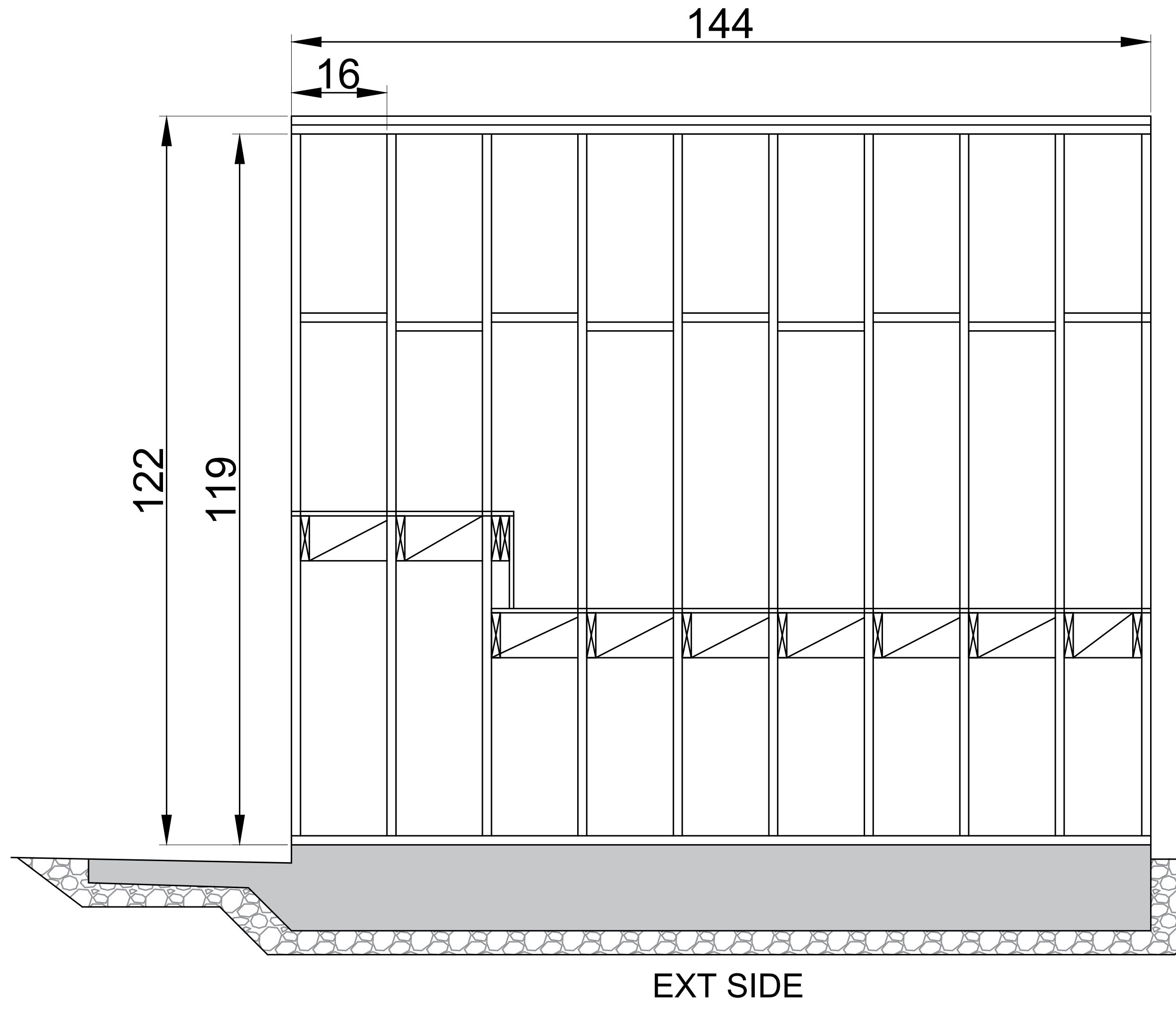

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General Notes

No.	Revision/Issue	Date
4	ADDED CONC. CURB & SLOPE	16/08/19
2	ADDED SLOPE, ROTATED BINS	24/07/19
1	BINS, PLYWOOD FINISH & AGENT	16/07/19

Firm Name and Address

Project Name and Address
COMPOSTING TOILET

Project
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Sheet
S1

Date
7/11/2019

Scale
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