Electronic Supplementary Material (ESI) for Environmental Science: Water Research & Technology.

SUPPORTING INFORMATION

Resource recovery technologies as microbial risk barriers: towards safe use of excreta in agriculture based on hazard analysis and critical control point

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R code for estimation of parameters of Hom's model

```
d<-data.frame(t,N)        # t: every sampling time (day), N: concentration of microorganisms at time t
params0 <- c(1,1,0.1)      # Default values of the estimates (k, m, sigma2)
# Function for optimization
f1 <- function(p, data) {
  parameters<-c(k=p[1], m=p[2], sigma2=p[3])
  rss<-data[1,2]*exp(-p[1]*data[,1]^p[2])+parameters[3]
  n<-length(data)
sum(-log(data[,2]))-(n/2)*log(2*pi*parameters[3])-1/2/parameters[3]*sum((log(rss)-log(data[,2]))^2)
}
fit0 <- optim(params0, f1, data=d, control=list(fnscale=-1))   # Optimization
fit0$convergence           # Confirm convergence
fit0$par                   # Output estimates
```

Figure S1: Temperature, pH, dilution ratio, and ammonia concentration of urine used in the literature we reviewed.

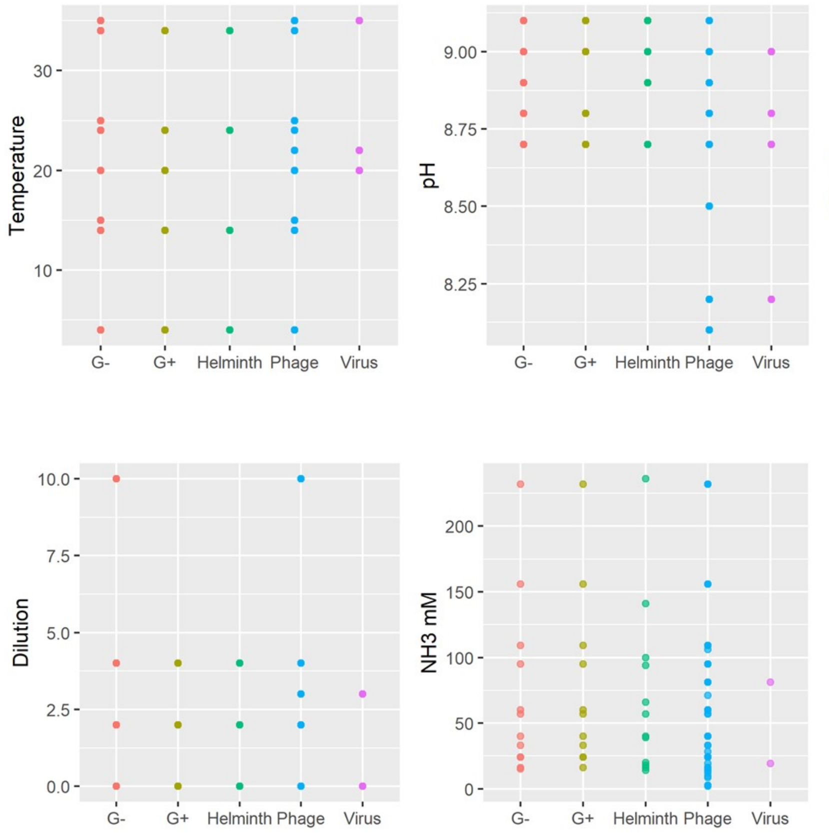

Table S1: Estimated storage time of urine to achieve the target log reduction values of microorganism during thermal storage and storage with the presence of sunlight.

Microorganisms	day	Temperature (°C)	Dilution ratio	Sunlight	References
Salmonella	0.15	65	0	Yes	Sangare et al., 2020
Salmonella	0.25	46	0	Yes	Sangare et al., 2020
E. coli	0.09	50	0	Yes	Sangare et al., 2020
E. coli	0.09	45	0	Yes	Sangare et al., 2020
E. coli	1	60	1.5	No	Zhou et al., 2017
E. coli	0.5	70	1.5	No	Zhou et al., 2017
Fecal coliforms	0.25	60	1.5	No	Zhou et al., 2017
Fecal coliforms	0.25	70	1.5	No	Zhou et al., 2017
Salmonella	0.2	29.1	0	Yes	Nordin et al., 2013
E. coli	0.2	29.1	0	Yes	Nordin et al., 2013

Enterococcus	15.4	28.1	0	Yes	Nordin et al., 2013
Enterococcus	3.6	29.1	0	Yes	Nordin et al., 2013
Ascaris egg	17	28.1	0	Yes	Nordin et al., 2013
MS2	41	29.1	0	Yes	Nordin et al., 2013
phiX174	185	29.1	0	Yes	Nordin et al., 2013
28B	275	29.1	0	Yes	Nordin et al., 2013

Figure S2: Conditions of fecal sludge (temperature, pH, moisture content, and ammonia concentration) in the literature we reviewed.

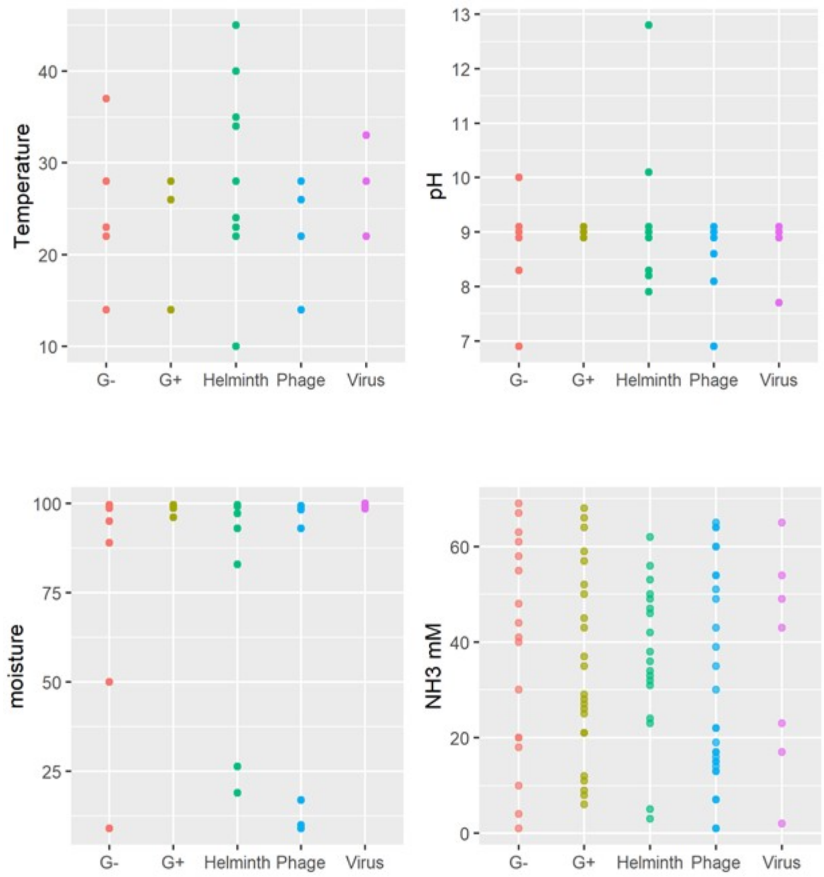

Table S2: Estimated time of fecal sludge to achieve the target log reduction values of *Ascaris* egg and phages.

Microorganisms	day	k (day^{-1})	m	Temperature (^{o}C)	pH	Moisture (%)	NH_3 (mM)	Desiccant	References
Ascaris egg	2	-	-	45	8.3	26.4	2.5	Dirt	Cruz Espinoza et al., 2012
Ascaris egg	42	-	-	35	8.3	26.4	1.5	Dirt	Cruz Espinoza et al., 2012
Ascaris egg	14	-	-	40	8.3	26.4	2	Dirt	Cruz Espinoza et al., 2012
Ascaris egg	5	1.7E+00	1.09	34	13	83	71	Ash	Nordin et al., 2009
Ascaris egg	49	2.4E-03	2.12	34	8.2	83	63	-	Nordin et al., 2009
Ascaris egg	115	3.1E-02	1.2	24	10	83	58	Ash	Nordin et al., 2009
Ascaris egg	63	7.4E-01	0.61	23	9.1	97.2	340	-	Fidjeland et al., 2013
Ascaris egg	38	5.2E-02	1.43	28	9.1	97.2	421	-	Fidjeland et al., 2013
Ascaris egg	46	1.3E-03	2.32	23	9.1	99.2	171	-	Fidjeland et al., 2013
Ascaris egg	42	2.7E-01	0.95	28	9.1	99.2	213	-	Fidjeland et al., 2013
Ascaris egg	44	1.5E-03	2.3	23	9.1	99.3	231	-	Fidjeland et al., 2013
Ascaris egg	38	7.3E-02	1.33	28	9.1	93	283	-	Fidjeland et al., 2013
Ascaris egg	47	9.7E-04	2.38	28	8.9	99.5	56	-	Fidjeland et al., 2013
Ascaris egg	93	6.6E-03	1.6	23	9	99.6	83	-	Fidjeland et al., 2013
Ascaris egg	51	6.3E-02	1.27	28	9	99.6	104	-	Fidjeland et al., 2013
Ascaris egg	188	7.8E-04	1.79	23	8.9	99.5	44	-	Fidjeland et al., 2013
Ascaris egg	452	4.8E-02	0.86	22	7.9	19	2.9	Oyster shells	Magri et al., 2013
Ascaris egg	516	5.7E-12	4.5	10	9.1	97.2	170	-	Fidjeland et al., 2013
MS2	120	7.3E-02	1.18	26	9.1	99	169	-	Magri et al., 2015
MS2	113	2.1E-02	1.46	26	9	98.8	135	-	Magri et al., 2015
MS2	125	2.2E-02	1.42	26	9.1	99	150	-	Magri et al., 2015
MS2	110	1.3E-04	2.55	26	9	98.3	89	-	Magri et al., 2015

MS2	183	8.0E-03	1.51	26	8.9	98.5	78	-	Magri et al., 2015
MS2	547	1.2E-01	0.82	26	9	98.5	69	-	Magri et al., 2015
MS2	287	9.8E-04	1.76	26	8.9	99.3	36	-	Magri et al., 2015
MS2	154	8.1E-02	1.1	22	8.6	10	11	Oyster shells	Magri et al., 2013
MS2	319	1.3E-01	0.884	22	6.9	9	0.2	-	Magri et al., 2013
PhiX174	22	1.2E-04	3.9	28	9.1	93	314	-	Magri et al., 2015
PhiX174	22	9.4E-06	4.8	28	8.9	98.8	155	-	Magri et al., 2015
PhiX174	90	1.9E-02	1.55	28	9	99	124	-	Magri et al., 2015
PhiX174	78	1.1E-03	2.26	28	9	98.3	124	-	Magri et al., 2015
PhiX174	98	9.4E-02	1.18	28	8.9	99.3	56	-	Magri et al., 2015
PhiX174	100	2.4E-03	1.97	28	9.1	99	225	-	Magri et al., 2015
PhiX174	162	3.8E-02	1.24	28	9	98.5	91	-	Magri et al., 2015
PhiX174	172	3.5E-02	1.24	28	9	98.5	130	-	Magri et al., 2015
PhiX174	406	2.1E-01	0.766	28	8.9	98.5	78	-	Magri et al., 2015
PhiX174	180	4.1E-02	1.2	26	9.1	99	169	-	Magri et al., 2015
PhiX174	191	3.8E-02	1.2	26	9	93	193	-	Magri et al., 2015
PhiX174	182	4.5E-02	1.18	26	9	98.8	135	-	Magri et al., 2015
PhiX174	255	1.2E-01	0.936	26	9.1	99	150	-	Magri et al., 2015
PhiX174	234	5.1E-02	1.1	26	9	98.3	89	-	Magri et al., 2015
PhiX174	215	1.1E-02	1.4	26	9	98.5	69	-	Magri et al., 2015
PhiX174	131	1.7E-01	0.99	22	8.6	10	11	Oyster shells	Magri et al., 2013
PhiX174	84	1.2E-01	1.17	22	8.1	17	6	Oyster shells	Magri et al., 2013
PhiX174	158	1.7E-02	1.4	22	6.9	9	0.2	-	Magri et al., 2013
PhiX174	204	4.4E-03	1.59	14	8.9	99.3	14	-	Magri et al., 2015

Figure S3: Bucket latrine. A bucket or pan is placed in a chamber below a pedestal or seat with a drop hole. When the bucket is full, it is taken out from the chamber through the rear flap and emptied.

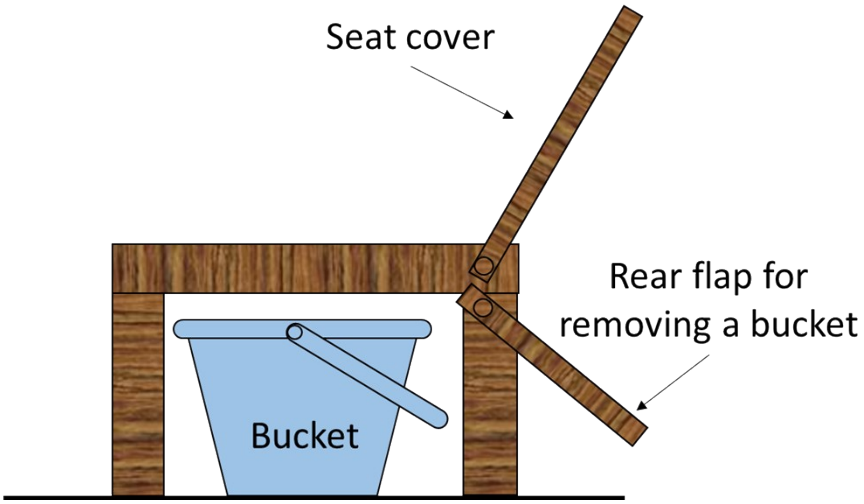

Figure S4: Single ventilated improved latrine (modified from Tilley et al. (2014)). Excreta, along with anal cleaning materials, are deposited into a pit. Typically, a pit is at least 3 m in depth and 1 m in diameter.

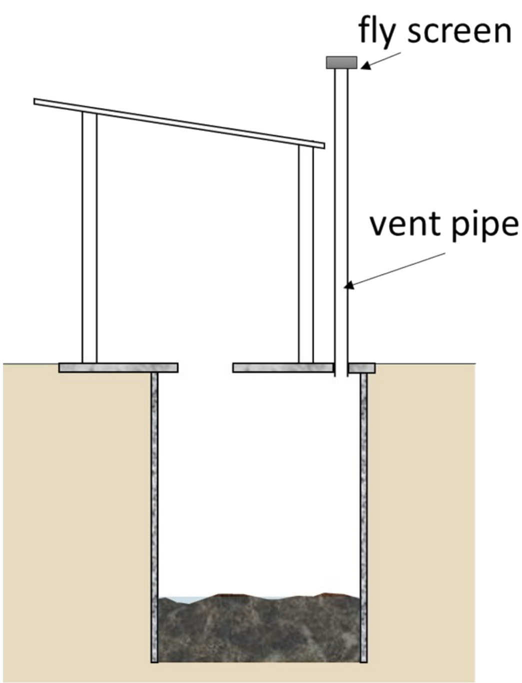

Figure S5: Septic tank (modified from Tilley et al. (2014)). A septic tank is a watertight chamber made of concrete, fibreglass, polyvinyl chloride, or plastic. The accumulated sludge and scum need to be periodically removed.

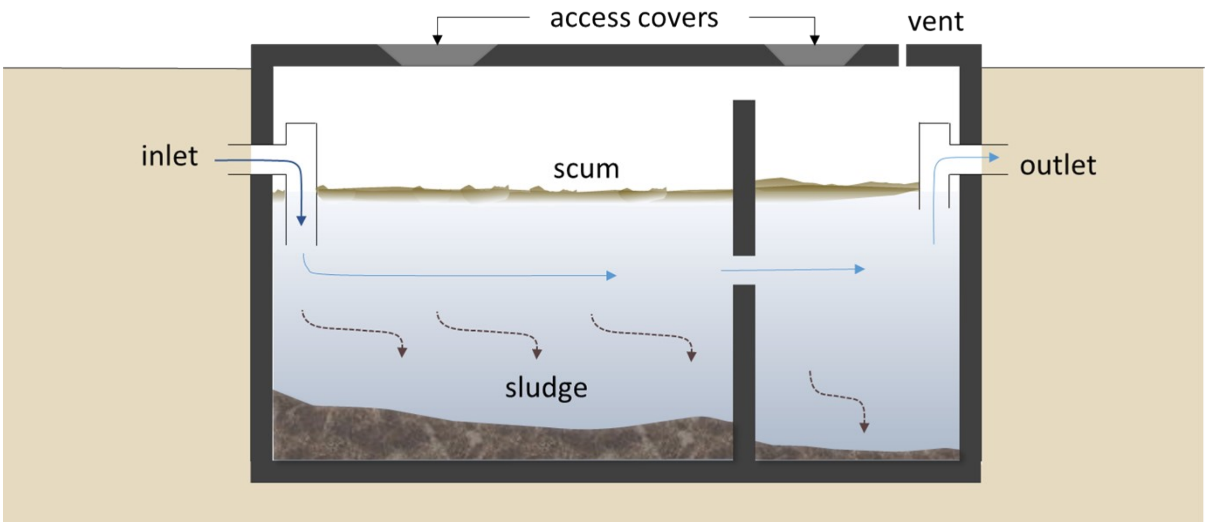

Figure S6: Twin pits and pour flush toilet (modified from Tilley et al. (2014)). Blackwater is collected in a leach pit and allowed to slowly infiltrate into the surrounding soil.

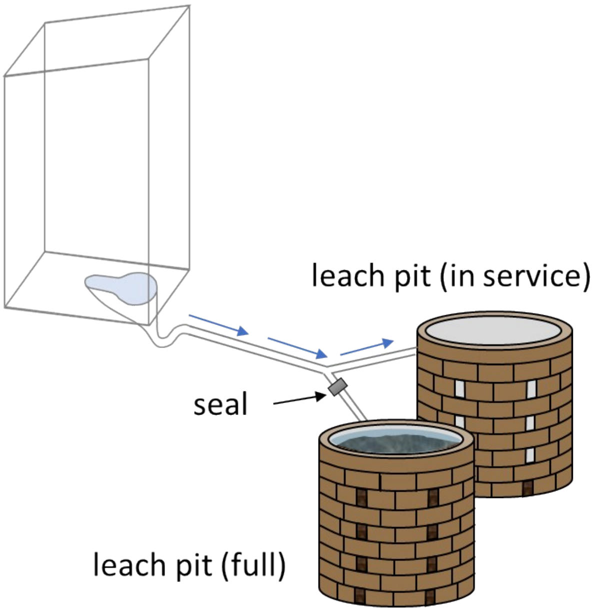

Figure S7: Double alternating dry pit (modified from Tilley et al. (2014)). One pit is used while the contents of another pit are partially sanitized for at least 1 to 2 years after several years of filling.

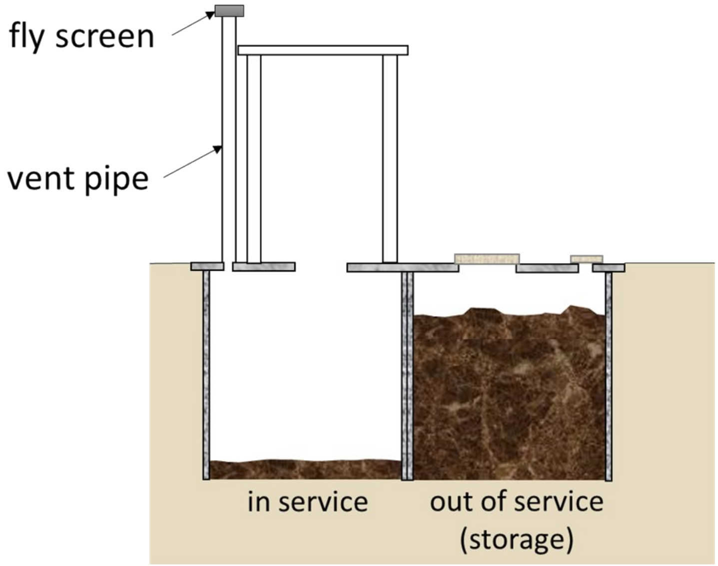

Figure S8: Double dehydration vaults (modified from Tilley et al. (2014)). Dehydration vaults are used to collect, store, and dry faces, whereas urine is separately collected in a urine tank.

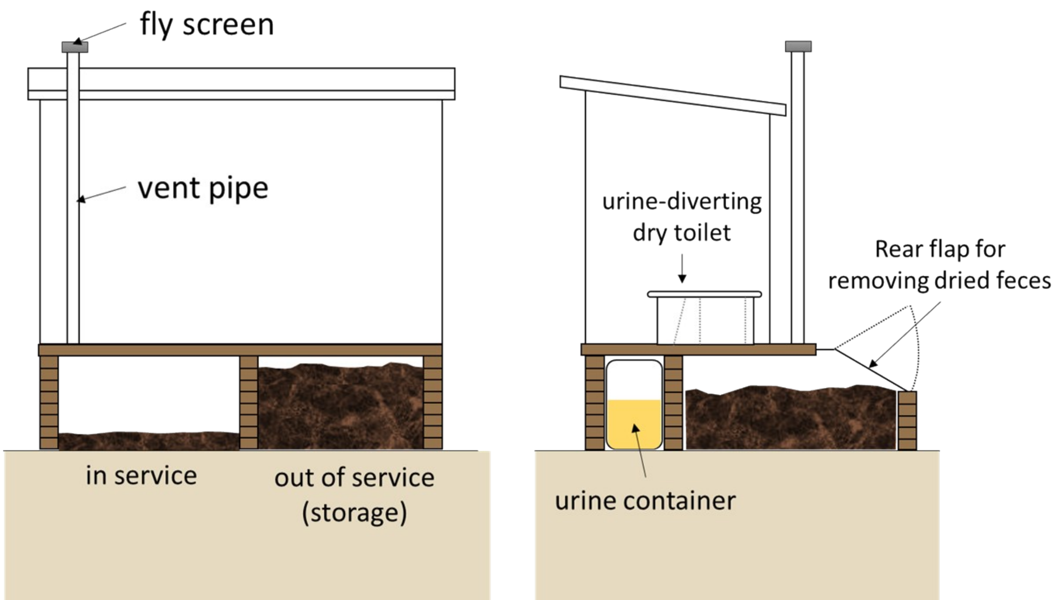

Table S3: Estimated storage time of fecal sludge to achieve the target log reduction values of microorganisms by lime addition.

Microorganisms	day	*k* (day^{-1})	*m*	Temperature (°C)	pH	Moisture (%)	NH_3 (mM)	Lime (wt%)	References
E. coli	1	1.4E+01	0.233	23	12.7	89	328	na	Ogunyoku et al., 2016
E. coli	0.2	1.3E-01	0.948	37	10	50	na	na	Hijikata et al., 2016
E. coli	0.1	2.6E-01	0.816	37	10.5	50	na	na	Hijikata et al., 2016
E. coli	0.2	3.3E-01	0.394	37	11	50	na	na	Hijikata et al., 2016
E. coli	0.6	2.0E+01	0.7	27	10.5	90	na	14%	Greya et al., 2016
E. coli	0.01	2.0E-02	1	27	11	90	na	16%	Greya et al., 2016
Fecal coliforms	0.021	-	-	21	12.9	94	na	10%	da Silva et al., 2018
Fecal coliforms	0.021	-	-	21	12.9	94	na	20%	da Silva et al., 2018
Fecal coliforms	0.021	-	-	21	12.9	94	na	30%	da Silva et al., 2018
Enterococcus	1	4.2E-01	0.153	37	8.1	60	0	1%	Darimani et al., 2015
Ascaris eggs	20	1.21E-05	2.2	23	12.8	89	464	na	Ogunyoku et al., 2016
MS2	2.3	1.2E+01	0.64	37	10	50	na	na	Hijikata et al., 2016
MS2	0.3	6.1E+01	0.86	37	10.5	50	na	na	Hijikata et al., 2016
MS2	0.2	8.8E+01	0.85	37	11	50	na	na	Hijikata et al., 2016
MS2	0.3	2.2E-01	0.69	23	12.5	89	36	na	Ogunyoku et al., 2016
MS2	26	3.7E-01	0.13	23	12.7	89	328	na	Ogunyoku et al., 2016
E. coli	51	6.3E+00	0.2	27	10	90	na	11%	Greya et al., 2016
Ascaris egg	7122	2.65E-01	0.1	23	12.8	89	50	na	Ogunyoku et al., 2016

Table S4: Estimated storage time of fecal sludge to achieve the target log reduction values of microorganisms by solar drying and pasteurization.

Microorganisms	day	*k* (day^{-1})	*m*	Temperature (^oC)	pH	Moisture (%)	Sunlight	References
E. coli	0.45	1.1E-01	0.7	75	7.4	10	Yes	Sossou et al., 2016
Enterococcus	0.65	6.9E-01	1.06	75	7.4	10	Yes	Sossou et al., 2016
E. coli	0.4	3.2E-02	0.78	50	na	50	No	Darimani et al., 2015
E. coli	0.0	6.25E-01	0.14	70	na	50	No	Darimani et al., 2015
Enterococcus	1.3	3.9E-02	0.8	50	na	50	No	Darimani et al., 2015
Enterococcus	0.2	2.8E-01	0.6	70	na	50	No	Darimani et al., 2015
Ascaris egg	0.4	4.0E-01	2.44	75	7.4	10	Yes	Sossou et al., 2016
Ascaris egg	0.3	8.8E-02	1	50	na	50	No	Darimani et al., 2016
Ascaris egg	0.2	1.6E-01	2.34	60	na	50	No	Darimani et al., 2016
MS2	0.9	-	-	50	na	70	No	Darimani et al., 2018
MS2	1.2	-	-	50	na	60	No	Darimani et al., 2018
MS2	3.8	-	-	50	na	50	No	Darimani et al., 2018
MS2	1.5	-	-	40	na	70	No	Darimani et al., 2018
MS2	2.3	-	-	40	na	60	No	Darimani et al., 2018
MS2	4.3	-	-	40	na	50	No	Darimani et al., 2018
Ascaris egg	220	-	-	31	6.7	19	Yes	Dey et al., 2016
E. coli	267	4.3E-05	2.27	31	6.7	19	Yes	Dey et al., 2016

Table S5: Estimated storage time of fecal sludge to achieve the target log reduction values of microorganisms by anaerobic digestion.

Microorganisms	day	k (day^{-1})	m	Temperature (^{o}C)	References
Ascaris egg	66	-	-	37	Kato et al., 2003
Ascaris egg	6	-	-	47	Kato et al., 2003
Ascaris egg	0.6	2.20E-01	1.44	54	Seruga et al., 2020
Ascaris egg	0.8	2.80E-01	1.19	54	Seruga et al., 2020
Ascaris egg	22.4	2.20E-02	1.95	40	Harroff et al., 2019
Ascaris egg	28	1.55E-03	2.61	39	Harroff et al., 2019
Ascaris egg	53	5.00E-04	2.48	37	Harroff et al., 2019
E. coli	462	-	-	28	Kearney et al., 1993
E. coli	51	-	-	25	Pandey and Soupir, 2011
E. coli	45	-	-	37	Pandey and Soupir, 2011
E. coli	3	-	-	52.5	Pandey and Soupir, 2011
Salmonella	210	-	-	28	Kearney et al., 1993
Salmonella	0.5	7.30E+00	0.25	54	Seruga et al., 2020
Salmonella	0.3	8.90E+00	0.21	54	Seruga et al., 2020
Enterococcus	0.5	7.20E+00	0.26	54	Seruga et al., 2020
Enterococcus	0.5	6.90E+00	0.27	54	Seruga et al., 2020
MS2	10	1.40E-01	2	35	Decrey and Kohn, 2017
MS2	4	4.00E+00	1	35	Decrey and Kohn, 2017
MS2	2	1.04E+01	0.4	35	Decrey and Kohn, 2017
MS2	2	6.20E+00	2.3	35	Decrey and Kohn, 2017
phiX174	214	1.90E+00	0.37	35	Decrey and Kohn, 2017
B40-8	414	9.60E-01	0.51	37	Baert et al., 2010
B40-8	466	1.67E+00	0.41	37	Baert et al., 2010
B40-8	83	2.00E+00	0.53	52	Baert et al., 2010
B40-8	10	-	-	52	Baert et al., 2010
Human adenovirus	19	1.34E+00	0.8	35	Decrey and Kohn, 2017
Human adenovirus	36	4.50E-02	1.6	35	Decrey and Kohn, 2017
Murine norovirus 1	38	1.63E+00	0.7	37	Baert et al., 2010
Murine norovirus 1	68.2	3.10E+00	0.45	37	Baert et al., 2010
Murine norovirus 1	21.4	3.20E+00	0.61	52	Baert et al., 2010
Murine norovirus 1	19.5	3.70E+00	0.58	52	Baert et al., 2010

References

1. Sangare D, Brou AL, Sou/dakoure M, Tagro P V. Urine treatment by solar disinfection for agriculture reuse purpose in a poor rural context: case of Burkina Faso. J Water, Sanit Hyg Dev. 2020;1–9.

2. Zhou X, Li Y, Li Z, Xi Y, Uddin SMN, Zhang Y. Investigation on microbial inactivation and urea decomposition in human urine during thermal storage. J Water Sanit Hyg Dev. 2017;7(3):378–86.

3. Nordin A, Niwagaba C, Jönsson H, Vinnerås B. Pathogen and indicator inactivation in source-separated human urine heated by the sun. J Water Sanit Hyg Dev. 2013;3(2):181–8.

4. Cruz Espinoza LM, Yeh D, Vinnerås B, Rajaram L, Corvin J, Izurieta R. Inactivation of ascaris suum by ammonia in feces simulating the parameters of the solar toilet. J Appl Sci Environ Sanit [Internet]. 2012;7(3):173–82. Available from: http://libproxy.lib.unc.edu/login?url=http://search.proquest.com/docview/912918996?accountid=14244

5. Nordin A, Nyberg K, Vinnerås B. Inactivation of ascaris eggs in source-separated urine and feces by ammonia at ambient temperatures. Appl Environ Microbiol. 2009;75(3):662–7.

6. Fidjeland J, Magri ME, Jönsson H, Albihn A, Vinnerås B. The potential for self-sanitisation of faecal sludge by intrinsic ammonia. Water Res. 2013;47(16):6014–23.

7. Magri ME, Philippi LS, Vinnerås B. Inactivation of pathogens in feces by desiccation and urea treatment for application in urine-diverting dry toilets. Appl Environ Microbiol. 2013;79(7):2156–63.

8. Magri ME, Fidjeland J, Jönsson H, Albihn A, Vinnerås B. Inactivation of adenovirus, reovirus and bacteriophages in fecal sludge by pH and ammonia. Sci Total Environ [Internet]. 2015;520:213–21. Available from: http://dx.doi.org/10.1016/j.scitotenv.2015.03.035

9. Tilley E, Ulrich L, Luethi C, Reymond P, Zurburegg C, Lüthi C, et al. Compendium of sanitation systems and technologies. Development. 2014;

10. Ogunyoku TA, Habebo F, Nelson KL. In-toilet disinfection of fresh fecal sludge with ammonia naturally present in excreta. J Water Sanit Hyg Dev. 2016;6(1):104–14.

11. Hijikata N, Tezuka R, Kazama S, Otaki M, Ushijima K, Ito R, et al. Bactericidal and virucidal mechanisms in the alkaline disinfection of compost using calcium lime and ash. J Environ Manage [Internet]. 2016;181:721–7. Available from: http://dx.doi.org/10.1016/j.jenvman.2016.08.026

12. Greya W, Thole B, Anderson C, Kamwani F, Spit J, Mamani G. Off-site lime stabilisation as an option to treat pit latrine faecal sludge for emergency and existing on-site sanitation systems. J Waste Manag. 2016;2016:1–8.

13. da Silva DTG, Dias E, Ebdon J, Taylor H. Assessment of recommended approaches for containment and safe handling of human excreta in emergency settings. PLoS One. 2018;13(7):1–20.

14. Darimani HS, Ito R, Sossou SK, Funamizu N, Amadou MH. Effect of post-treatment conditions on the inactivation rate of pathogenic bacteria after the composting process. Compost Sci Util. 2015;23(3):164–73.

15. Sossou SK, Sou/Dakouré M, Hijikata N, Maiga AH, Funamizu N. Inactivation kinetics of indicator microorganisms during solar heat treatment for sanitizing compost from composting toilet. J Water Environ Technol. 2016;14(2):37–46.

16. Darimani HS, Ito R, Maiga, Ynoussa, Sou M, Funamizu N, Maiga AH. Effect of post-treatment conditions on the inactivation of helminth eggs (Ascaris suum) after the composting process. Environ Technol. 2016;37:920–928.

17. Darimani HS, Ito R, Funamizu N, Maiga AH. Effect of post-treatment conditions on the inactivation of MS2 bacteriophage as indicator for pathogenic viruses after the composting process. J Agric Chem Environ. 2018;07(02):73–80.

18. Dey D, Ridwanul ATMH, Kabir B, Ubaid SF. Fecal indicator and Ascaris removal from double pit latrine content. J Water Health. 2016;14(6):972–9.

19. Kato S, Fogarty E, Bowman D. Effect of aerobic and anaerobic digestion on the viability of Cryptosporidium parvum oocysts and Ascaris suum eggs. Int J Environ Health Res. 2003;13(2):169–79.

20. Seruga P, Krzywonos M, Paluszak Z, Urbanowska A, Pawlak-Kruczek H, Niedźwiecki Ł, et al. Pathogen reduction potential in anaerobic digestion of organic fraction of municipal solid waste and food waste. Molecules. 2020;25(2):1–13.

21. Harroff LA, Liotta JL, Bowman DD, Angenent LT. Current time-temperature relationships for thermal inactivation of Ascaris eggs at mesophilic temperatures are too conservative and may hamper development of simple, but effective sanitation. Water Res X [Internet]. 2019;5:100036. Available from: https://doi.org/10.1016/j.wroa.2019.100036

22. Kearney TE, Larkin MJ, Levett PN. The effect of slurry storage and anaerobic digestion on survival of pathogenis bacteria. J Appl Bacteriol. 1993;74:86–93.

23. Pandey PK, Soupir ML. Escherichia coli inactivation kinetics in anaerobic digestion of dairy

manure under moderate, mesophilic and thermophilic temperatures. AMB Express. 2011;1(1):1–10.

24. Decrey L, Kohn T. Virus inactivation in stored human urine, sludge and animal manure under typical conditions of storage or mesophilic anaerobic digestion. Environ Sci Water Res Technol. 2017;3(3):492–501.

25. Baert L, De Gusseme B, Boon N, Verstraete W, Debevere J, Uyttendaele M. Inactivation of murine norovirus 1 and Bacteroides fragilis phage B40-8 by mesophilic and thermophilic anaerobic digestion of pig slurry. Appl Environ Microbiol. 2010;76(6):2013–7.