URINE **PROCESSING**

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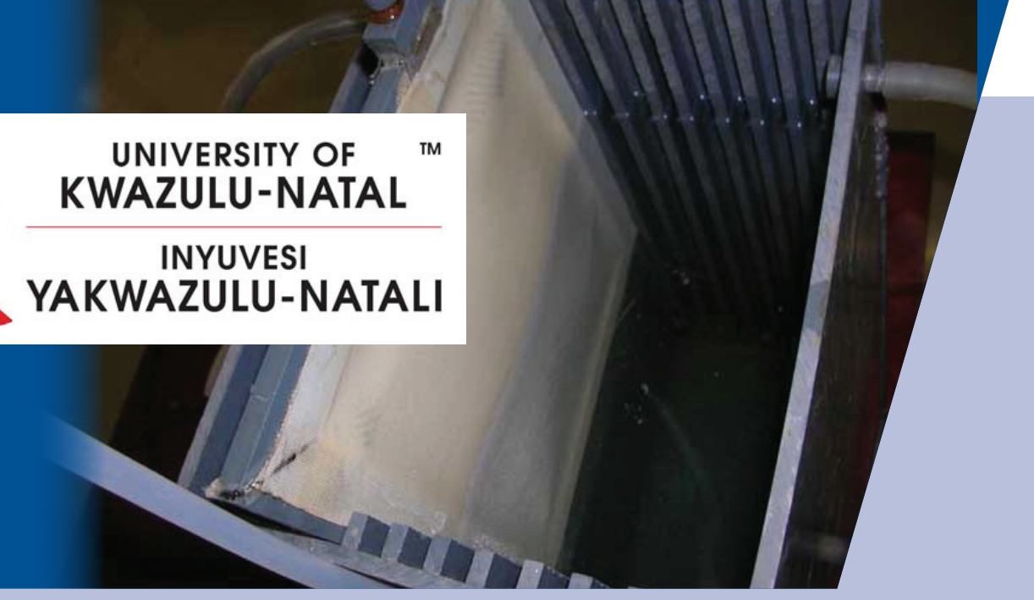


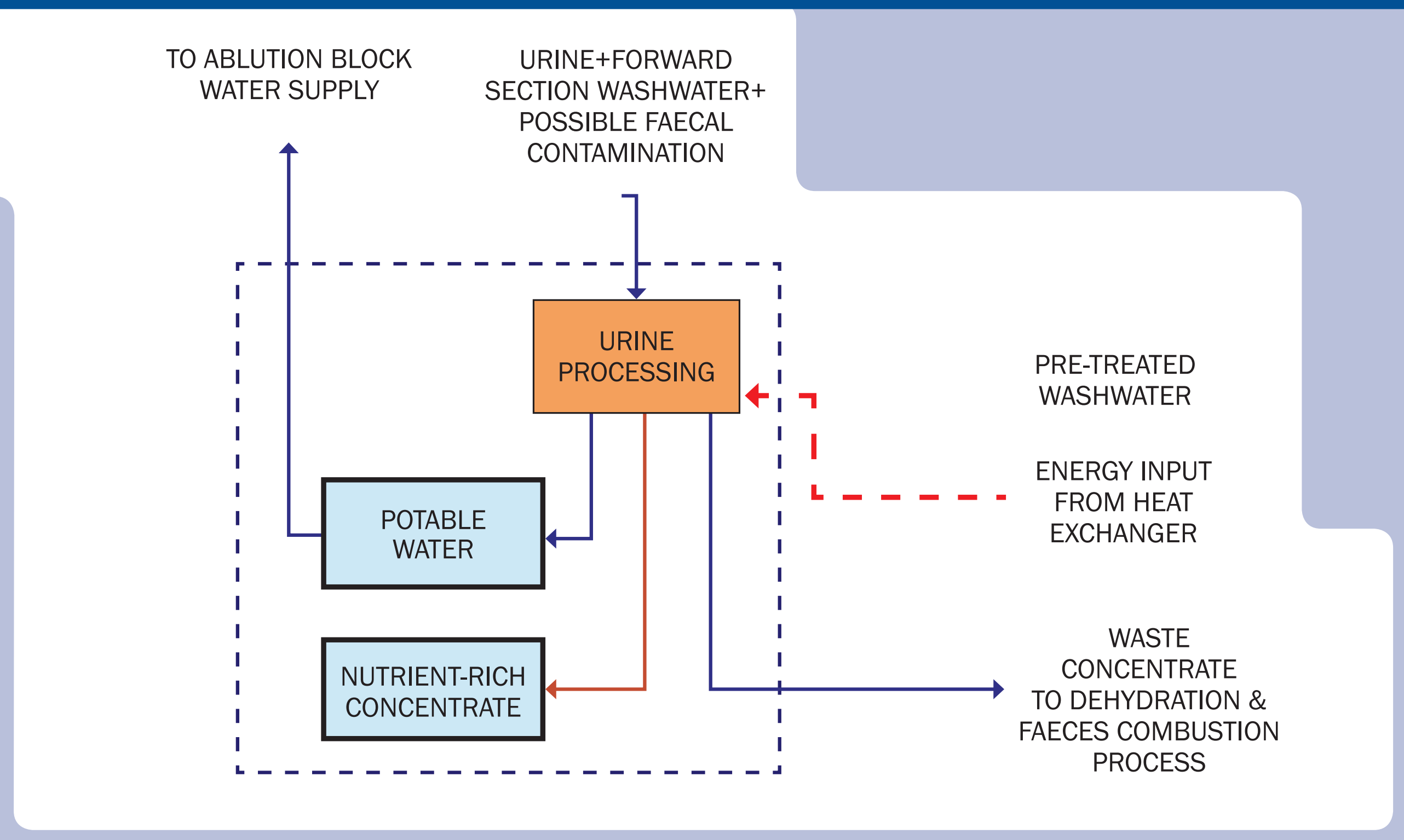


FIGURE 1 URINE PROCESSING HIGH LEVEL PROCESS FLOW DIAGRAM

DESIGN OBJECTIVES

- **Recovery of potable water**
- **Production of a sterile, nutrient-rich product in a form suitable for agricultural applications**
- **Treatment of liquid waste streams from other unit operations of the toilet**

CONCEPT

The system under study is a three-stage membrane system, with a feed of urine diluted with a small amount of wash water from the forward section of the toilet pedestal. The system will eventually also accept pre-treated wash water from the rear section of the pedestal, at the stage of the process where the two streams are of most similar composition (to be determined).

DESIGN PRINCIPLES

Maintain streams in as concentrated form as possible

Combine streams for processing when compositions are as similar as possible

Use low grade heat (readily available from other parts of the toilet process) as the power source where possible

Failsafe process – will function with a urine feed contaminated with faecal material and washwater

Robust and modular process – simple to maintain

No regular addition of non-standard consumables (e.g. chemical dosing agents) required

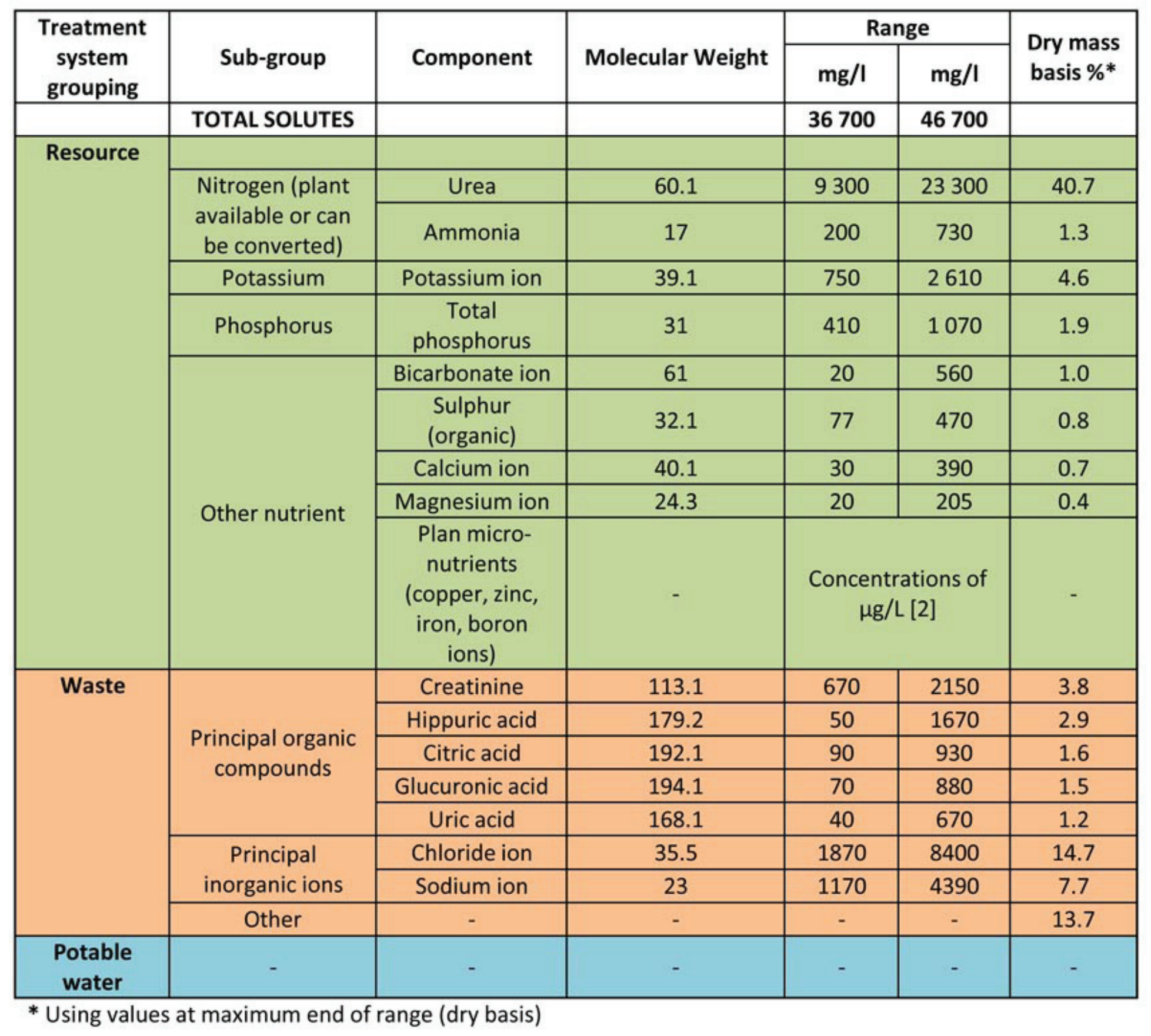
Process to be universal - not dependent on geographical location, time of day or season (e.g. availability of solar radiation)

Influent stream separation requirements

The urine processing system will separate urine into potable water, a concentrated resource stream and a concentrated waste stream. Urine contains, on average, 80 % of the nitrogen and 50 % of the phosphorus excreted from the human body [1]. Nitrogen, phosphorous and potassium are present in urine in forms that can readily be taken up by plants [2]. Recovery of these components provides the opportunity to

(i) produce an agricultural product with an economic value and (ii) close the nutrient cycle on non-renewable phosphorus [3]. The waste components that should be separated from urine before it can be used as a fertiliser product include sodium chloride, pharmaceutical compounds and endocrine disruptors. Table 1 summarises the principal components of fresh urine, grouped in the categories of interest for the treatment system (resource, waste, potable water). Note in unstabilised, stored urine the urea and uric acid have in the majority decomposed and the majority of nitrogen is present as ammoniacal N [2].

TABLE 1 Components of urine ([4], unlesss otherwise indicated) grouped into categories of relevance for the processing system



Treatment system grouping	Sub-group	Component	Molecular Weight	Range mg/l	Range mg/l	Dry mass basis %*
	TOTAL SOLUTES			36 700	46 700	
Resource						
	Nitrogen (plant available or can be converted)	Urea	60.1	9 300	23 300	40.7
		Ammonia	17	200	730	1.3
	Potassium	Potassium ion	39.1	750	2 610	4.6
	Phosphorus	Total phosphorus	31	410	1 070	1.9
	Other nutrient	Bicarbonate ion	61	20	560	1.0
		Sulphur (organic)	32.1	77	470	0.8
		Calcium ion	40.1	30	390	0.7
		Magnesium ion	24.3	20	205	0.4
		Plan micro-nutrients (copper, zinc, iron, boron ions)	-	Concentrations of μg/L [2]		-
Waste	Principal organic compounds	Creatinine	113.1	670	2150	3.8
		Hippuric acid	179.2	50	1670	2.9
		Citric acid	192.1	90	930	1.6
		Glucuronic acid	194.1	70	880	1.5
		Uric acid	168.1	40	670	1.2
	Principal inorganic ions	Chloride ion	35.5	1870	8400	14.7
		Sodium ion	23	1170	4390	7.7
	Other	-	-	-	-	13.7
Potable water	-	-	-	-	-	-

* Using values at maximum end of range (dry basis)

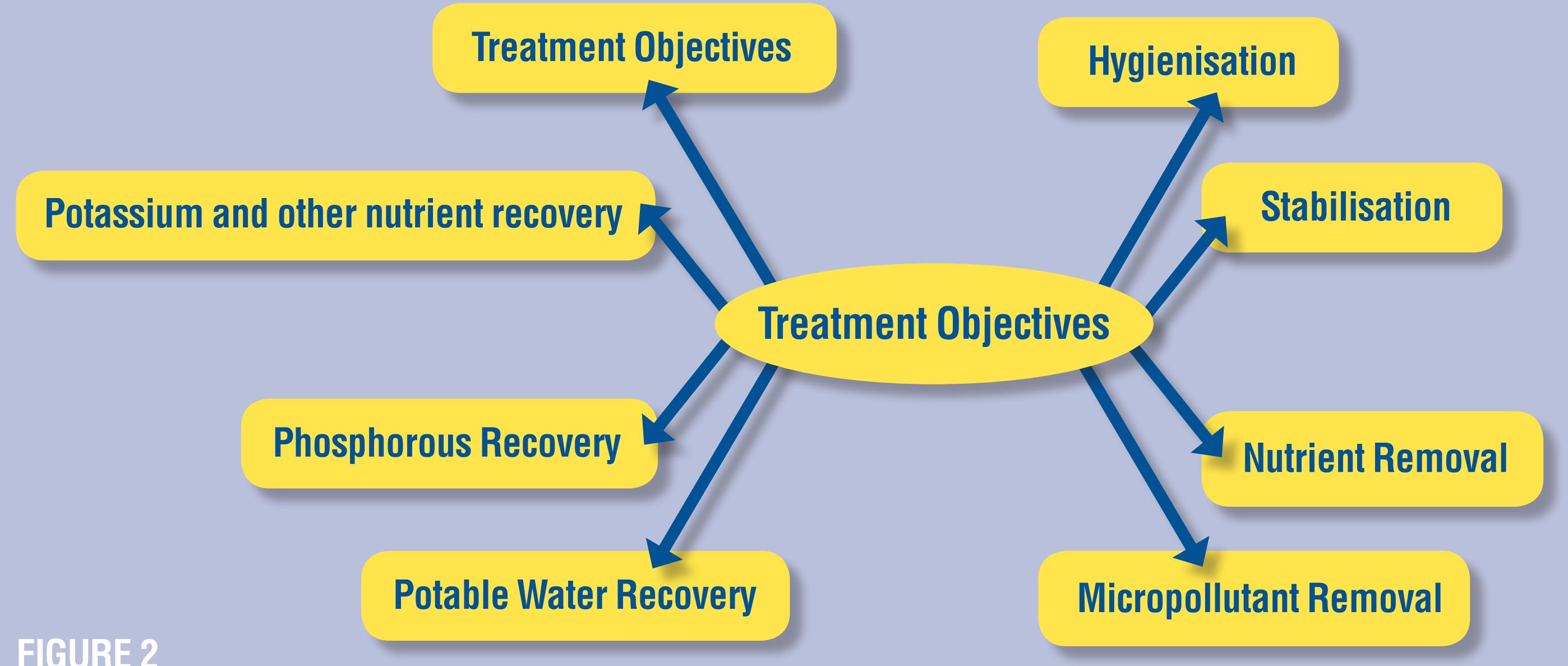
PROCESS SELECTION

A two-stage screening process was used to select potential processes that would fulfil the design objectives: (i) Screening against the treatment process objectives and (ii) Screening against design constraints.

Figure 2 provides a detailed breakdown of the potential objectives of treating urine. Nutrient removal is relevant to non-RTTC contexts where a waste stream will be discharged to the environment.

Thirty different processes were judged against the extent to which they fulfilled these objectives, with the screening process summarised in Table 2. The second stage screening against the design constraints is summarised in Figure 3.

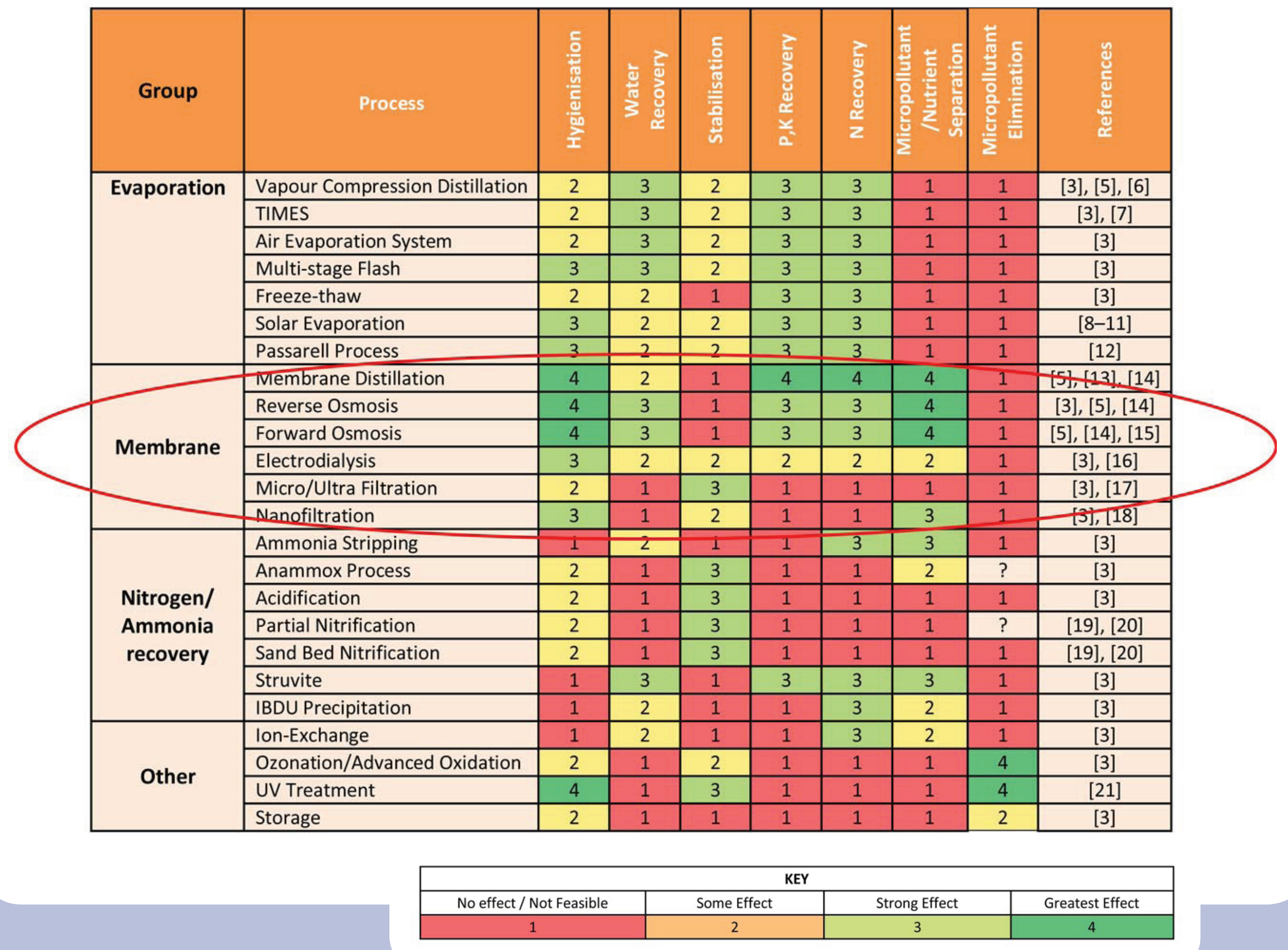
Evaporation systems score well against the treatment objectives, but are highly energy-intensive. Membrane systems achieved the best scores across the broadest range of treatment objectives, and the majority of the design constraints do not apply. Energy requirements of membrane systems vary by the membrane used.



Treatment Objectives
Hygienisation
Potassium and other nutrient recovery
Stabilisation
Treatment Objectives
Phosphorous Recovery
Nutrient Removal
Potable Water Recovery
Micropollutant Removal

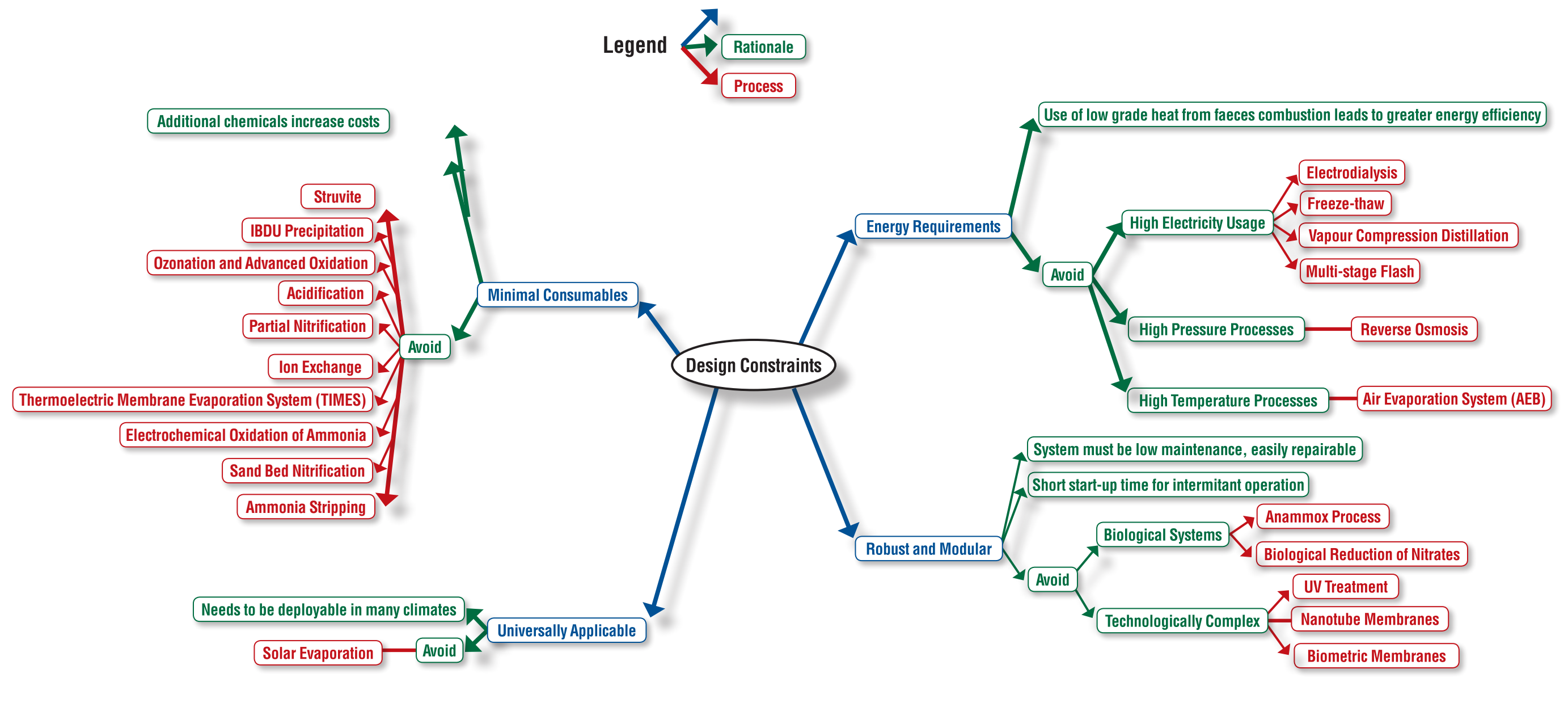
FIGURE 2
POSSIBLE OBJECTIVES OF URINE TREATMENT PROCESSES

TABLE 2 SCREENING SELECTION TABLE OF PROCESSES FOR URINE TREATMENT



Group	Process	Hygienisation	Water Recovery	Stabilisation	P,K Recovery	N Recovery	Micropollutant /Nutrient Separation	Micropollutant Elimination	References
Evaporation	Vapour Compression Distillation	2	3	2	3	3	1	1	[3], [5], [6]
	TIMES	2	3	2	3	3	1	1	[3], [7]
	Air Evaporation System	2	3	2	3	3	1	1	[3]
	Multi-stage Flash	3	3	2	3	3	1	1	[3]
	Freeze-thaw	2	2	1	3	3	1	1	[3]
	Solar Evaporation	3	2	2	3	3	1	1	[8–11]
	Passarell Process	3	2	2	3	3	1	1	[12]
Membrane	Membrane Distillation	4	2	1	4	4	4	1	[5], [13], [14]
	Reverse Osmosis	4	3	1	3	3	4	1	[3], [5], [14]
	Forward Osmosis	4	3	1	3	3	4	1	[5], [14], [15]
	Electrodialysis	3	2	2	2	2	2	1	[3], [16]
	Micro/Ultra Filtration	2	1	3	1	1	1	1	[3], [17]
	Nanofiltration	3	1	2	1	1	3	1	[3], [18]
Nitrogen/ Ammonia recovery	Ammonia Stripping	1	2	1	1	3	3	1	[3]
	Anammox Process	2	1	3	1	1	2	?	[3]
	Acidification	2	1	3	1	1	1	1	[3]
	Partial Nitrification	2	1	3	1	1	1	?	[19], [20]
	Sand Bed Nitrification	2	1	3	1	1	1	1	[19], [20]
	Struvite	1	3	1	3	3	3	1	[3]
	IBDU Precipitation	1	2	1	1	3	2	1	[3]
Other	Ion-Exchange	1	2	1	1	3	2	1	[3]
	Ozonation/Advanced Oxidation	2	1	2	1	1	1	4	[3]
	UV Treatment	4	1	3	1	1	1	4	[21]
	Storage	2	1	1	1	1	1	2	[3]

KEY			
No effect / Not Feasible	Some Effect	Strong Effect	Greatest Effect
1	2	3	4



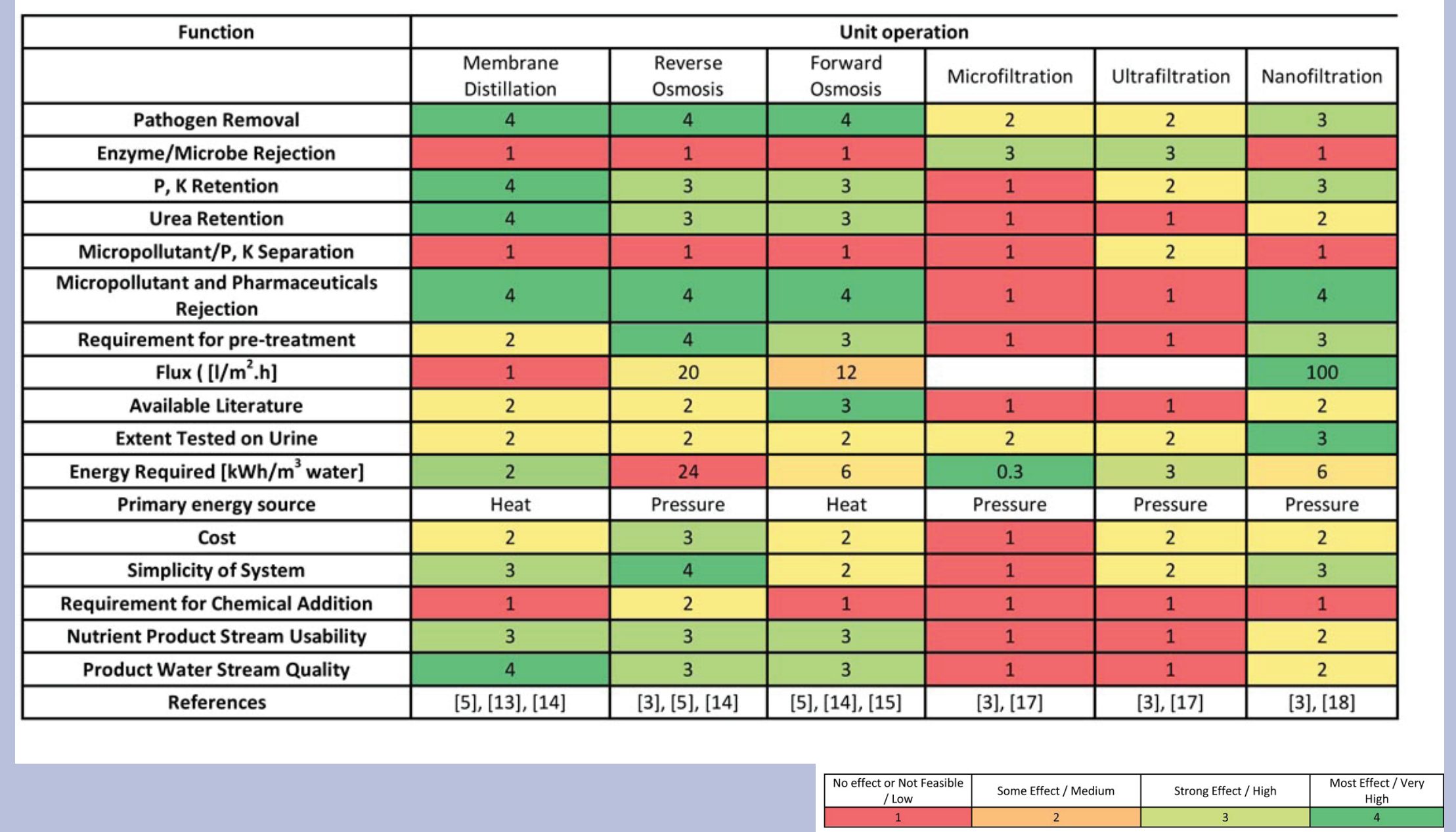
Legend
Rationale
Process
Design Constraints
Minimal Consumables
Additional chemicals increase costs
Avoid
Struvite
IBDU Precipitation
Ozonation and Advanced Oxidation
Acidification
Partial Nitrification
Ion Exchange
Thermoelectric Membrane Evaporation System (TIMES)
Electrochemical Oxidation of Ammonia
Sand Bed Nitrification
Ammonia Stripping
Universally Applicable
Needs to be deployable in many climates
Avoid
Solar Evaporation
Energy Requirements
Use of low grade heat from faeces combustion leads to greater energy efficiency
Avoid
High Electricity Usage
Electrodialysis
Freeze-thaw
Vapour Compression Distillation
Multi-stage Flash
High Pressure Processes
Reverse Osmosis
High Temperature Processes
Air Evaporation System (AEB)
Robust and Modular
System must be low maintenance, easily repairable
Short start-up time for intermitant operation
Avoid
Biological Systems
Anammox Process
Biological Reduction of Nitrates
Technologically Complex
UV Treatment
Nanotube Membranes
Biometric Membranes

FIGURE 3 SCREENING OF PROCESSES AGAINST DESIGN CONSTRAINTS

SELECTION OF MEMBRANE PROCESSES

Table 3 compares the ability of different membranes to separate the principal components of urine, based on previous work using membranes to treat raw and diluted urine.

TABLE 3 comparison of membrane processes

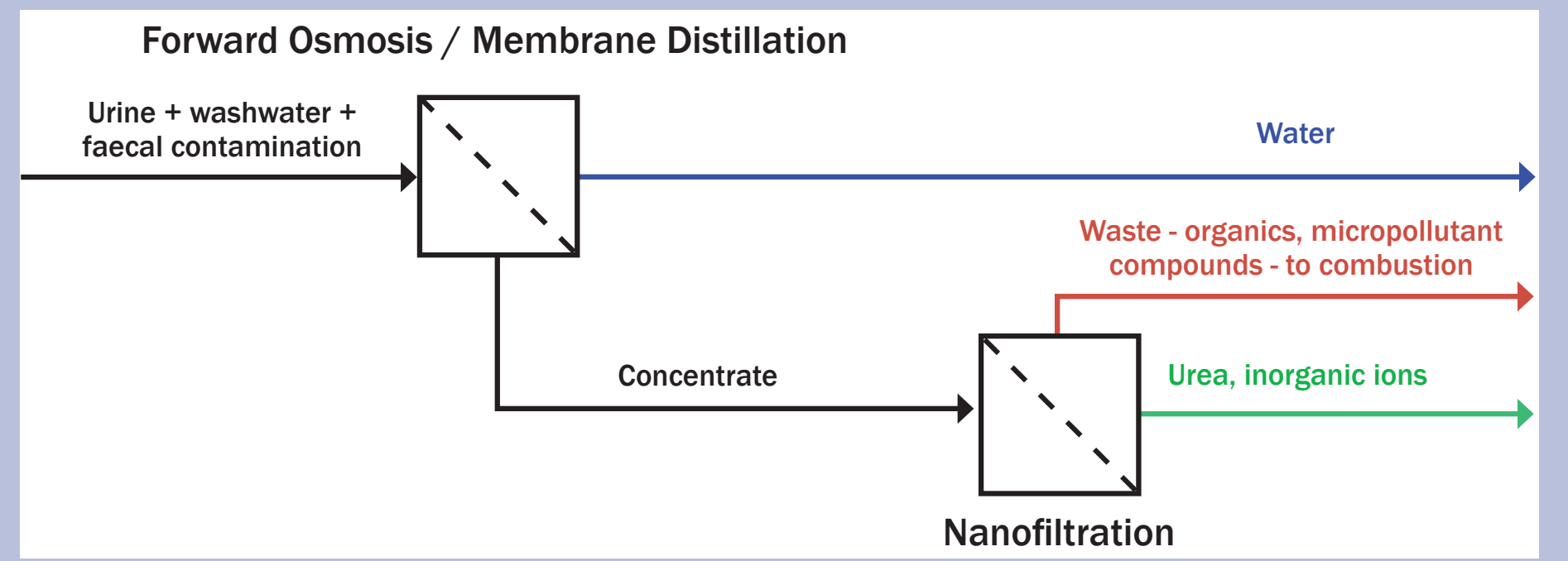


Function	Unit operation					
	Membrane Distillation	Reverse Osmosis	Forward Osmosis	Microfiltration	Ultrafiltration	Nanofiltration
Pathogen Removal	4	4	4	2	2	3
Enzyme/Microbe Rejection	1	1	1	3	3	1
P, K Retention	4	3	3	1	2	3
Urea Retention	4	3	3	1	1	2
Micropollutant/P, K Separation	1	1	1	1	2	1
Micropollutant and Pharmaceuticals Rejection	4	4	4	1	1	4
Requirement for pre-treatment	2	4	3	1	1	3
Flux ([l/m^2.h]	1	20	12			100
Available Literature	2	2	3	1	1	2
Extent Tested on Urine	2	2	2	2	2	3
Energy Required [kWh/m^3 water]	2	24	6	0.3	3	6
Primary energy source	Heat	Pressure	Heat	Pressure	Pressure	Pressure
Cost	2	3	2	1	2	2
Simplicity of System	3	4	2	1	2	3
Requirement for Chemical Addition	1	2	1	1	1	1
Nutrient Product Stream Usability	3	3	3	1	1	2
Product Water Stream Quality	4	3	3	1	1	2
References	[5], [13], [14]	[3], [5], [14]	[5], [14], [15]	[3], [17]	[3], [17]	[3], [18]

No effect or Not Feasible / Low	Some Effect / Medium	Strong Effect / High	Most Effect / Very High
1	2	3	4

Three different process combinations were considered, with the product, waste and water streams (colour coded according the groupings given in Table 1) being recovered at different stages.

(1) **Recovery of water; secondary separation of concentrate into waste and urea**

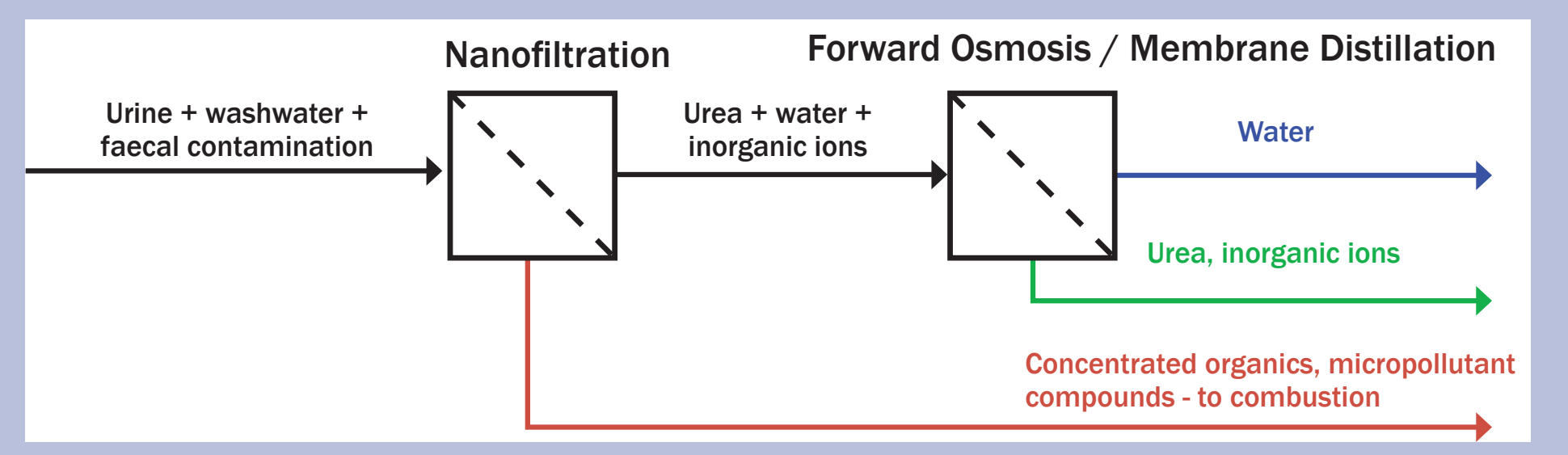


Forward Osmosis / Membrane Distillation
Urine + washwater + faecal contamination
Water
Waste - organics, micropollutant compounds - to combustion
Concentrate
Urea, inorganic ions
Nanofiltration

FIGURE 4 PROCESS COMBINATION 1 – PROCESS FLOW DIAGRAM

The first approach would separate the water first, possibly using a combination of forward osmosis and membrane distillation. The logic behind this was to concentrate all the nutrients into one stream making fertiliser production easier. The problem with this process flow would be fouling at the first stage, if membranes were used, as all the organics and salts would still be present. Lower flux across the membrane due to fouling would lead to lower recovery rates and higher energy requirements.

(2) **Primary separation of waste components, secondary separation of water and urea**

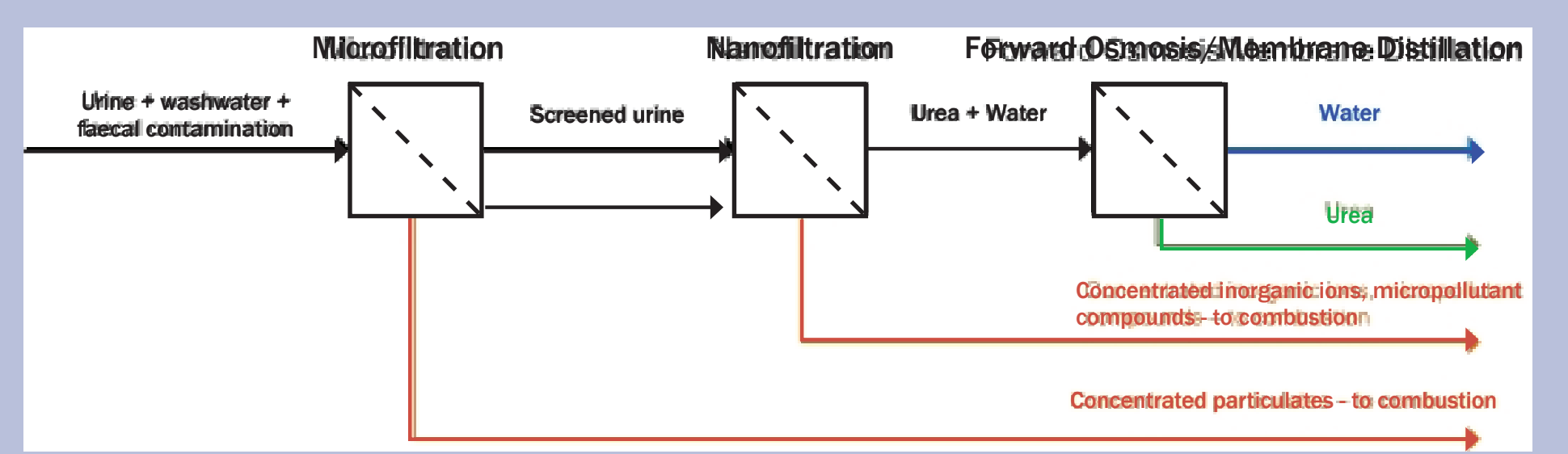


Nanofiltration
Forward Osmosis / Membrane Distillation
Urine + washwater + faecal contamination
Urea + water + inorganic ions
Water
Urea, inorganic ions
Concentrated organics, micropollutant compounds - to combustion

FIGURE 5 PROCESS COMBINATION 2 – PROCESS FLOW DIAGRAM

The second approach would decrease the fouling potential at the first stage by use of a nanofiltration membrane, which is more resistant to fouling. The benefits of the scheme would again be the concentration of all desired products for fertiliser production in one stream. The problem with the second process flow would be achieving the necessary split between the waste components and the desired components with agricultural value in the concentrate stream from the nanofiltration stage.

(3) **Removal of potential fouling components, secondary separation of waste components, tertiary separation of water and urea**



Microfiltration
Nanofiltration
Forward Osmosis/Membrane Distillation
Urine + washwater + faecal contamination
Screened urine
Urea + Water
Water
Urea
Concentrated inorganic ions, micropollutant compounds - to combustion
Concentrated particulates - to combustion

FIGURE 6 PROCESS COMBINATION 3 – PROCESS FLOW DIAGRAM

The third approach uses three different membrane units in sequence. The first stage – microfiltration (MF) or loose ultrafiltration (UF) - acts as a screening step to remove particulates and organic components which could cause fouling downstream. The nanofiltration (NF) stage provides separation of the waste components, including most of the salts and the majority of the pharmaceuticals [18]. A final forward osmosis (FO) stage (or combination of forward osmosis and membrane distillation) splits urea from water [5], [14], [15]. The process should be able to accept the various feed solutions that might have to be accepted by the urine processing unit within the toilet - including fresh and aged urine as well as urine contaminated with faecal matter. Figures 7 to 8 give a visual indication of the different levels of fouling that might be expected from these feeds.

Figure 7
Fresh urine

Figure 7
Contaminated stored urine in field storage tank [24]

Figure 8
Figure 8 aged urine [23]

Figure 9
Urine with faecal contamination collected from community ablution block

The microfiltration, ultrafiltration and nanofiltration processes would require some energy to produce the necessary pressures, typically around 0.3 kWh/m3 of feed for MF and 6 kWh/m3 for NF [3]. The advantage of the forward osmosis process, used in the final step, is that the driving energy required can primarily be supplied from the low-grade heat available from the combustor section of the toilet.

DESIGN DATA REQUIREMENTS

The membrane systems must be designed to (i) separate components as desired; (ii) achieve a sufficient level of throughput and (iii) not use excessive amounts of energy.

The following design data are required:

Expected compositions of different urine feeds (fresh, aged, contaminated with faecal material)

- Data on segregated fresh [4] and aged urine is readily available but the possibility of faecal contamination in the toilet must still be accounted for.

Fouling rates and reduction in fouling after cleaning

- Pronk et al. (2006) [18] considered the use of nanofiltration to treat fresh and synthetic urine feeds and achieved potassium and phosphate rejections of 65% and 95% respectively, and various pharmaceutical compound rejection upwards of 85% at a pH of 5.
- No data was found in the literature on fouling rates for membranes used in a forward osmosis process with a urine feed. McCutcheon et al. (2006) investigated the use of a forward osmosis process for the desalination of sea water ([22],[15]). Fouling rates were low, due to low-pressure operation, but greater fouling rates would be expected with a urine feed.

Recovery and rejection rates of solutes and water

- Microfiltration is commonly used to treat waste water instead of granular media filtration and ozone treatment units [17]. Using microfiltration to remove particulates from urine is likely to be effective but no data has been found in the literature on rejection rates of organic particulates with a urine-only feed.
- Pronk et al. (2006) [18] investigated the use of nanofiltration with fresh and synthetic urine feeds and achieved potassium and phosphate rejections of 65% and 95% respectively, and various pharmaceutical compound rejection upwards of 85% at a pH of 5.
- Production of potable water from sea water [15], [22] using forward osmosis is well documented, with water recovery of up to 70%, solute rejections of 95% and fluxes up to 25 l/m2.h[15]. The use of forward osmosis for urine treatment has not been widely studied. A few studies ([5], [14]) using forward osmosis to treat a urine feed indicate that there is some promise with rejection of urea upwards of 99% when used in conjunction with membrane distillation.

Flux through the membranes

- The flux through the forward osmosis stage will be the rate limiting factor to the process. Flux across the FO membrane is expected to be around 1l/m2.h ([5], [14

EXPERIMENTAL WORK

Laboratory-scale testing will be carried out on microfiltration, nanofiltration and forward osmosis membrane systems to produce the design data outlined above. Figures 11 – 13 summarise the experimental setups to be used.

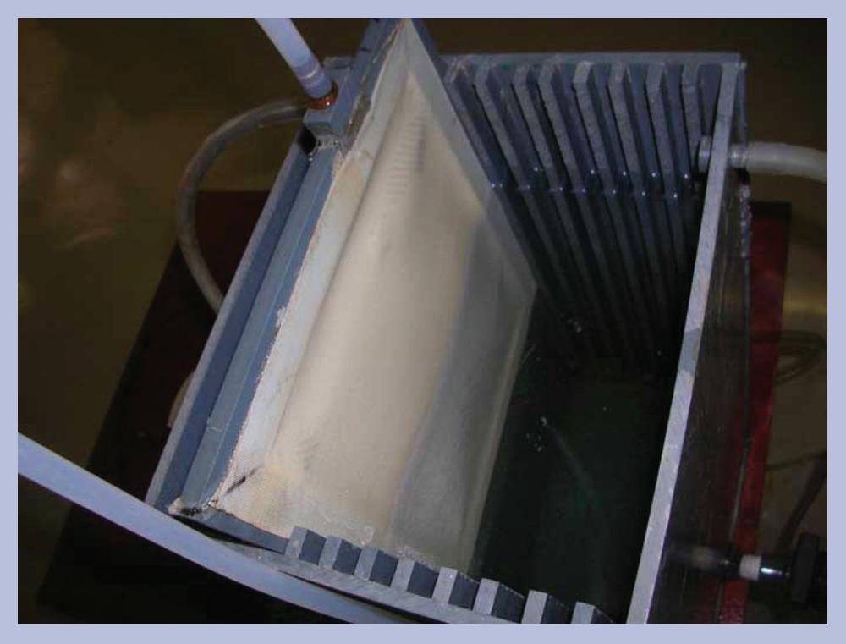


FIGURE 11
MICROFILTRATION MEMBRANES

FIGURE 12
NANOFILTRATION EXPERIMENTAL RIG

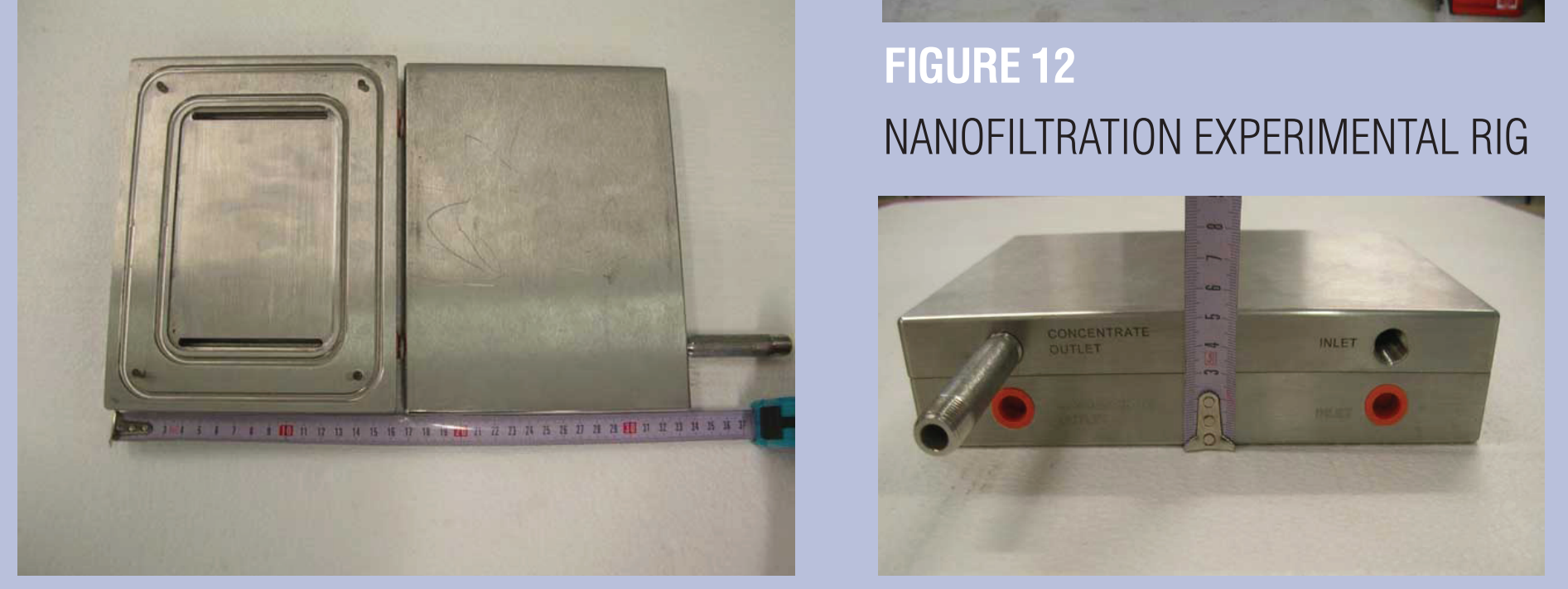


FIGURE 13 FORWARD OSMOSIS MEMBRANE CELL

References

Backhurst, JR & Harker, JH 1975, 'Evaluation of Physical Properties of Pig Manure', J. agric. Engng Res., vol. 19, pp. 199-207.

References

[1] W. Pronk and D. Koné, "Options for urine treatment in developing countries," Desalination, vol. 248, no. 1–3, pp. 360–368, Nov. 2009.
[2] H. Kirchmann and S. Pettersson, "Human urine-chemical composition and fertilizer use efficiency," Nutrient Cycling in Agroecosystems, vol. 40, no. 2, pp. 149–154, 1994.
[3] M. Maurer, W. Pronk, and T. A. Larsen, "Treatment processes for source-separated urine," Water Research, vol. 40, no. 17, pp. 3151–3166, Oct. 2006.
[4] J. F. Parker, V. R. West, B. inc, and U. S. O. of N. Research, Bioastronautics data book. Scientific and Technical Information Office, National Aeronautics and Space Administration; [for sale by the Supt. of Documents, U.S. Govt. Print. Off.], 1973.
[5] T. Y. Cath, S. Gormly, E. G. Beaudry, M. T. Flynn, V. D. Adams, and A. E. Childress, "Membrane contactor processes for wastewater reclamation in space," Journal of Membrane Science, vol. 257, no. 1–2, pp. 85–98, Jul. 2005.
[6] S. B. Sears, "Vapor Compression Distillation," Water Conditioning and Purification, 2006.
[7] United Technologies Corporation, "US Patent 4316774 - Thermoelectric integrated membrane evaporation system." [Online]. Available: http://www.wikipatents.com/US-Patent-4316774/thermoelectric-integrated-membrane-evaporation-system. [Accessed: 21-Jun-2012].
[8] S. Antonini, P. T. Nguyen, U. Arnold, T. Eichert, and J. Clemens, "Solar thermal evaporation of human urine for nitrogen and phosphorus recovery in Vietnam," Science of The Total Environment, vol. 414, pp. 592–599, Jan. 2012.
[9] D. Bahnemann, "Photocatalytic water treatment: solar energy applications," Solar Energy, vol. 77, no. 5, pp. 445–459, Nov. 2004.
[10] S. Malato, J. Blanco, D. C. Alarcón, M. I. Maldonado, P. Fernández-Ibáñez, and W. Gernjak, "Photocatalytic decontamination and disinfection of water with solar collectors," Catalysis Today, vol. 122, no. 1–2, pp. 137–149, Apr. 2007.
[11] S. Malato, P. Fernández-Ibáñez, M. I. Maldonado, J. Blanco, and W. Gernjak, "Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends," Catalysis Today, vol. 147, no. 1, pp. 1–59, Sep. 2009.
[12] Water Desalination International, "Passarell Process," Water Desalination International. [Online]. Available: http://www.waterdesalination.com/technica.htm. [Accessed: 18-Jul-2012].
[13] A. Criscuoli, M. C. Carnevale, and E. Drioli, "Energy requirements in membrane distillation: evaluation and optimization," Desalination, vol. 200, no. 1–3, pp. 586–587, Nov. 2006.
[14] T. Y. Cath, D. Adams, and A. E. Childress, "Membrane contactor processes for wastewater reclamation in space," Journal of Membrane Science, vol. 257, no. 1–2, pp. 111–119, Jul. 2005.
[15] T. Cath, A. Childress, and M. Elimelech, "Forward osmosis: Principles, applications, and recent developments," Journal of Membrane Science, vol. 281, no. 1–2, pp. 70–87, Sep. 2006.
[16] W. Pronk, M. Biebow, and M. Boller, "Electrodialysis for Recovering Salts from a Urine Solution Containing Micropollutants," Environmental Science & Technology, vol. 40, no. 7, pp. 2414–2420, Apr. 2006.
[17] WasteWater System, "WasteWater System: Microfiltration Membrane System," WasteWater System. [Online]. Available: http://www.wastewatersystem.net/2010/01/microfiltration-membrane-system.html. [Accessed: 17-Jul-2012].
[18] W. Pronk, H. Palmquist, M. Biebow, and M. Boller, "Nanofiltration for the separation of pharmaceuticals from nutrients in source-separated urine," Water Research, vol. 40, no. 7, pp. 1405–1412, Apr. 2006.
[19] D. Feng, Z. Wu, and S. Xu, "Nitrification of human urine for its stabilization and nutrient recycling," Bioresource Technology, vol. 99, no. 14, pp. 6299–6304, Sep. 2008.
[20] K. M. Udert and M. Wächter, "Complete nutrient recovery from source-separated urine by nitrification and distillation," Water Research, vol. 46, no. 2, pp. 453–464, Feb. 2012.
[21] X. Liu, M. Chen, Z. Bian, and C. Liu, "Studies on urine treatment by biological purification using Azolla and UV photocatalytic oxidation," Advances in Space Research, vol. 41, no. 5, pp. 783–786, Jan. 2008.
[22] J. R. McCutcheon, R. L. McGinnis, and M. Elimelech, "Desalination by ammonia–carbon dioxide forward osmosis: Influence of draw and feed solution concentrations on process performance," Journal of Membrane Science, vol. 278, no. 1–2, pp. 114–123, Jul. 2006.
[23] Grau, M. (2012). Stored Urine. Urine. At: Durban: University of KwaZulu Natal, Pollution Research Group
[24] Grau, M. (2012). Contaminated Urine. Urine. At: Durban: University of KwaZulu Natal, Pollution Research Group