**Supporting Information**

# Life Cycle Assessment of Advanced Nutrient Removal Technologies for Wastewater Treatment

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**Table S1.** Characteristics of treatment selected treatment plants with process configurations and technology alternatives to achieve different nutrient treatment levels

| Treatment Level | Plant ID | Chemical Addition | Secondary with Nutrient Removal process | Tertiary processes |
|---|---|---|---|---|
| Level 1 | NRP_Chem1 | $FeCl_3$ in Primary clarifier | Modified Ludzack-Ettinger (MLE) | -- |
| | NRP_Chem2 | $FeCl_3$ in Secondary with nutrient removal process | Modified Ludzack-Ettinger (MLE) | -- |
| | NRP_Chem3 | $FeCl_3$ in Primary clarifier and Secondary with nutrient removal process | Modified Ludzack-Ettinger (MLE) | -- |
| | BNR1 | -- | 5-stage Bardenpho | -- |
| | BNR2 | -- | University of Cape Town process | -- |
| | BNR_Chem1 | $FeCl_3$ in Primary clarifier | 5-stage Bardenpho | -- |
| | BNR_Chem2 | $FeCl_3$ in Primary clarifier | University of Cape Town process | -- |
| Level 2 | BNR1_EC_Fil1 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Filtration |
| | BNR2_EC_Fil1 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Filtration |
| | BNR1_EC_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $FeCl_3$ in tertiary process | 5-stage Bardenpho | Filtration with continuous backwash |
| | BNR2_EC_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $FeCl_3$ in tertiary process | University of Cape Town process | Filtration with continuous backwash |
| | BNR1_EC_Sed1 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Sedimentation |
| | BNR2_EC_Sed1 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Sedimentation |

| Treatment Level | Plant ID | Chemical Addition | Secondary with Nutrient Removal process | Tertiary processes |
|---|---|---|---|---|
| | BNR1_EC_Sed2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Ballasted Sedimentation |
| | BNR2_EC_Sed2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Ballasted Sedimentation |
| | MBR1_EC | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Membrane Filtration |
| | MBR2_EC | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Membrane Filtration |
| Level 3 | BNR1_EC_Fil1_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Filtration with continuous backwash; Filtration |
| | BNR2_EC_Fil1_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Filtration with continuous backwash; Filtration |
| | BNR1_EC_Sed1_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Sedimentation; Filtration with continuous backwash |
| | BNR2_EC_Sed1_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Sedimentation; Filtration with continuous backwash |
| | BNR1_EC_Sed2_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Ballasted Sedimentation; Filtration with continuous backwash |
| | BNR2_EC_Sed2_Fil2 | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Ballasted Sedimentation; Filtration with continuous backwash |

| Treatment Level | Plant ID | Chemical Addition | Secondary with Nutrient Removal process | Tertiary processes |
|---|---|---|---|---|
| | BNR1_EC_Sed2_MF | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Sedimentation; Membrane Filtration |
| | BNR2_EC_Sed2_MF | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Sedimentation; Membrane Filtration |
| | BNR1_EC_MF_RO | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | 5-stage Bardenpho | Membrane filtration; Reverse Osmosis |
| | BNR2_EC_MF_RO | $FeCl_3$ in Primary clarifier, methanol in Secondary with nutrient removal, $Al_2(SO_4)_3$ in tertiary process | University of Cape Town process | Membrane filtration; Reverse Osmosis |

**Table S2.** Design Criteria and Material, Chemical and Energy Inventory Basis of the Treatment Processes

| Process | Design criteria | Material inventory and basis |
|---|---|---|
| Primary clarifier | Surface overflow rate: 800-1000 gal/ $ft^2$.d<br>Retention time: 2-2.5 hrs. | Concrete & steel: based on size of the clarifier. Volume of concrete and steel were normalized to the per $m^3$ of wastewater treated by dividing with total volume of water treated in its lifetime of 20 years<br>Operation energy: energy required to operate the clarifier collected from literature [1-2]<br>Chemical: when chemical P removal was intended $FeCl_3$ is added as coagulant. Loading of Ferric are estimated from the BioWin design data |
| Secondary with nutrient removal process | SRT: 10 days<br>MLSS: 2000-2500 mg/L | Concrete & steel: based on size of the reactor designed in BioWin. Volume of concrete and steel were normalized to the per $m^3$ of wastewater treated by dividing with total volume of water treated in its lifetime of 20 years<br>Operation Energy: Energy for recycle flows, aeration, are calculated based on the BioWin design data<br>Chemical: Methanol is added when external carbon is required for advanced nutrients (both N and P) removal. The loads are estimated using BioWin model data<br>Ferric is added for chemical P removal (when necessary). |
| Secondary clarifier | Surface overflow rate: 400-700 gal/ $ft^2$.d<br>Retention time: 2-2.5 hrs. | Concrete, Steel and Operation energy are estimated as the primary clarifier. No chemical is added. |
| Filtration | Filtration rate: 80-400 $L/m^2$.min;<br>Sand layer depth: 360 mm (conventional); 1200 mm (deep-bed) | Energy is estimated from the literature [1-2]<br>Chemical: Alum is added to traditional filtration and $FeCl_3$ is added to filtration with continuous backwash process. The chemical loads are collected from the literature [3-5] |
| Enhanced Sedimentation | Flow rate: 10-15 gal/ $ft^2$.min | Energy is estimated from the literature [1-2]<br>Chemical: Alum is added for P removal which is collected from literatures [3-4,6-7] |
| Membrane filtration | Flux rate: 10-40 gal/ $ft^2$.d | Energy is estimated from the literature [1-2]<br>Chemical: Alum is added for P removal which is collected from literatures [3-4], NaOCl for membrane cleaning [8] |
| Reverse osmosis | Flux rate: 8-12 gal/ $ft^2$.d | Energy is collected from the literature [1-2] |

Reactor sizes are determined from the BioWin design. By using typical reactor wall thickness and roof properties, and reinforcement steel usages, volume and weight of concrete and steels are estimated from the designed rector size.

**Table S3.** Life cycle inventories per m$^3$ of influent wastewater

| Level | Plant ID | Electricity kWh | Concrete m$^3$ | Steel kg | $FeCl_3$ g | $Al_2(SO_4)_3$ g | Methanol g | NaOCl g |
|---|---|---|---|---|---|---|---|---|
| Level 1 | NRP_Chem1 | 0.28 | 1.345E-05 | 2.110E-03 | 26.12 | -- | -- | -- |
| | NRP_Chem2 | 0.28 | 1.345E-05 | 2.110E-03 | 26.12 | -- | -- | -- |
| | NRP_Chem3 | 0.28 | 1.345E-05 | 2.110E-03 | 26.12 | -- | -- | -- |
| | BNR1 | 0.29 | 1.804E-05 | 2.831E-03 | -- | -- | -- | -- |
| | BNR2 | 0.35 | 1.710E-05 | 2.684E-03 | -- | -- | -- | -- |
| | BNR_Chem1 | 0.29 | 1.804E-05 | 2.831E-03 | 8.71 | -- | -- | -- |
| | BNR_Chem2 | 0.35 | 1.710E-05 | 2.684E-03 | 8.71 | -- | -- | -- |
| Level 2 | BNR1_EC_Fil1 | 0.30 | 1.817E-05 | 2.851E-03 | 8.71 | 30.40 | 15.50 | -- |
| | BNR2_EC_Fil1 | 0.35 | 1.723E-05 | 2.704E-03 | 8.71 | 30.40 | 17.00 | -- |
| | BNR1_EC_Fil2 | 0.30 | 1.831E-05 | 2.874E-03 | 31.05 | -- | 15.50 | -- |
| | BNR2_EC_Fil2 | 0.35 | 1.738E-05 | 2.726E-03 | 31.05 | -- | 17.00 | -- |
| | BNR1_EC_Sed1 | 0.30 | 1.819E-05 | 2.854E-03 | 8.71 | 136.80 | 15.50 | -- |
| | BNR2_EC_Sed1 | 0.35 | 1.725E-05 | 2.707E-03 | 8.71 | 136.80 | 17.00 | -- |
| | BNR1_EC_Sed2 | 0.30 | 1.818E-05 | 2.852E-03 | 8.71 | 153.90 | 15.50 | -- |
| | BNR2_EC_Sed2 | 0.35 | 1.724E-05 | 2.705E-03 | 8.71 | 153.90 | 17.00 | -- |
| | MBR1_EC | 0.40 | 1.804E-05 | 2.831E-03 | 8.71 | 6.30 | 15.50 | 5.00 |
| | MBR2_EC | 0.45 | 1.710E-05 | 2.684E-03 | 8.71 | 6.30 | 17.00 | 5.00 |
| Level 3 | BNR1_EC_Sed1_Fil2 | 0.30 | 1.846E-05 | 2.897E-03 | 31.05 | 136.80 | 22.00 | -- |
| | BNR2_EC_Sed1_Fil2 | 0.36 | 1.752E-05 | 2.750E-03 | 31.05 | 136.80 | 23.60 | -- |
| | BNR1_EC_Sed2_Fil2 | 0.30 | 1.845E-05 | 2.895E-03 | 31.05 | 153.90 | 22.00 | -- |
| | BNR2_EC_Sed2_Fil2 | 0.36 | 1.751E-05 | 2.748E-03 | 31.05 | 153.90 | 23.60 | -- |
| | BNR1_EC_Fil1_Fil2 | 0.30 | 1.844E-05 | 2.893E-03 | 31.05 | 30.40 | 22.00 | -- |
| | BNR2_EC_Fil1_Fil2 | 0.36 | 1.750E-05 | 2.746E-03 | 31.05 | 30.40 | 23.60 | -- |
| | BNR1_EC_Sed2_MF | 0.41 | 1.818E-05 | 2.852E-03 | 8.71 | 160.20 | 22.00 | 5.00 |
| | BNR2_EC_Sed2_MF | 0.46 | 1.724E-05 | 2.705E-03 | 8.71 | 160.20 | 23.60 | 5.00 |
| | BNR1_EC_MF_RO | 2.40 | 1.804E-05 | 3.321E-03 | 8.71 | 6.30 | 22.00 | 5.00 |
| | BNR2_EC_MF_RO | 2.45 | 1.710E-05 | 3.174E-03 | 8.71 | 6.30 | 23.60 | 5.00 |

**Table S4.** Chemical Doses and P Removal Rate in Tertiary Processes[3-4]

| Treatment Processes | $FeCl_3$ | $Al_2(SO_4)_3$ | NaOCl | Removal Rate |
|---|---|---|---|---|
| | g/ $m^3$ WW | g/ $m^3$ WW | g/ $m^3$ WW | % |
| Filtration | -- | 30. | -- | 81 |
| Filtration with continuous backwash | 22 | -- | -- | 96 |
| Sedimentation | -- | 137 | -- | 97 |
| Ballasted Sedimentation | -- | 154 | -- | 93 |
| Membrane Filtration | -- | 6 | 5 | 94 |
| Reverse Osmosis | -- | -- | -- | 99 |

**Table S5.** List of Matched U.S.-EI 2.2 Unit Processes

| Item | U.S.-EI 2.2 unit processes used in LCA model |
|---|---|
| Electricity | Electricity mix/US with US electricity |
| Concrete | Concrete, normal, at plant/ CH U with US electricity |
| Reinforcing steel | Reinforcing Steel , at plant/ RER U with US electricity |
| $FeCl_3$ | Iron (III) chloride, 40% in $H_2O$, at plant/ CH with US electricity U |
| $Al_2(SO_4)_3$ | Aluminium sulphate, powder, at plant/ RER with US electricity U |
| Methanol | Methanol, at plant/ GLO with US electricity U |
| NaOCl | Sodium hypochlorite, 15% in $H_2O$, at plant/RER with US electricity U |

**Table S6.** List of LCA Impact Categories Analyzed in the Current Study

| Impact Categories | Unit | Rationale/Approach | References |
|---|---|---|---|
| Eutrophication potential | kg N eq. | Based on the potency of causing eutrophication in water body. It measures the equivalent eutrophication of a chemical in terms of nitrogen | 9-10 |
| Acidification potential | mol $H^+$ eq. | Based on the potential wet or dry acid deposition in atmosphere. Acidification potential is characterized by equivalent mol of $H^+$. | 9-11 |
| Global warming potential | kg $CO_2$ eq. | Global warming based on chemical's radiative force and lifetime in atmosphere. Global warming potency of a chemical is expressed as that of equivalent $CO_2$ | 9-11 |
| Ozone depletion potential | kg CFC-11 eq. | Based on chemical's reactivity and potential to destroy ozone in atmosphere. Ozone depletion is characterized by comparing to CFC-11 equivalency. | 9-11 |
| Ecotoxicity Potential | CTUe | Based on the potency of causing ecological harm in air, water, soil. It estimates the potentially affected fraction of species (PAF) integrated over time | 9,12 |
| Human-carcinogenic potential | CTUh | Based on the potential of causing cancer when a chemical is released to the air, water or soil. It is estimated by cancer related morbidity increase in the total human population per unit mass of an emitted chemical. | 9,12 |
| Human non-carcinogenic potential | CTUh | Potential of non-cancer related health effects from chemical emission. It is estimated by morbidity increase due to non-cancer related effects in the total human population per unit mass of an emitted chemical | 9,12 |

**Table S7.** Ranges of parameters for Uncertainty Analysis

| **Processes** | **$FeCl_3$** | | **$Al_2(SO_4)_3$** | | **Additional Electricity** | |
|---|---|---|---|---|---|---|
| | **g/ $m^3$ WW** | | **g/ $m^3$ WW** | | **kWh/$m^3$** | |
| | **Min** | **Max** | **Min** | **Max** | **Min** | **Max** |
| Filtration | -- | -- | 24 | 36 | 0.003 | 0.005 |
| Filtration with continuous backwash | 17.9 | 26.8 | -- | -- | 0.004 | 0.007 |
| Sedimentation | -- | -- | 72 | 200 | 0.004 | 0.008 |
| Ballasted Sedimentation | -- | -- | 57 | 250 | 0.004 | 0.008 |
| Membrane filtration | -- | -- | 5 | 8 | 0.07 | 0.14 |
| Reverse Osmosis | -- | -- | | | 1.5 | 3 |

Additionally, methanol is added to simulate the uncertainty involved with influent C to P ratio (C/P). Design C/P ratio is 25 and C/P of the worst case scenario is assumed to be 15. Methanol requirement to raise the C/P ratio from 15 to 25 is 80 mg/L for the influent selected in the study. Hence the range of uncertainty for methanol addition is 0 to 80 mg/L for each of the plants.

**Table S8.** Life Cycle Impact Assessment Results for the Base-case scenario with Activated Sludge Process

| Impact category | Total | Material | Chemical Secondary | Electricity Secondary | Effluent | Chemical Primary | Electricity Primary | Direct Emission |
|---|---|---|---|---|---|---|---|---|
| Eutrophication (kg N eq) | 0.0546 | 0 | 0 | 0.0005 | 0.0541 | 0 | 0 | 0 |
| Global warming (kg CO2 eq) | 0.2300 | 0.0065 | 0 | 0.1373 | 0 | 0 | 0.0042 | 0.0819 |
| Acidification (kg SO2 eq) | 9.9E-4 | 2.2E-5 | 0 | 9.4E-4 | 0 | 0 | 2.8E-5 | 0 |
| Ozone depletion (kg CFC-11 eq) | 6.7E-9 | 2.9E-10 | 0 | 6.2E-9 | 0 | 0 | 1.9E-10 | 0 |
| Ecotoxicity (CTUe) | 0.138 | 0.029 | 0 | 0.105 | 0 | 0 | 0.003 | 0 |
| Carcinogenics (CTUh) | 1.0E-8 | 2.9E-9 | 0 | 7.0E-9 | 0 | 0 | 2.1E-10 | 0 |
| Non carcinogenics (CTUh) | 7.2E-9 | 2.0E-9 | 0 | 5.1E-9 | 0 | 0 | 1.5E-10 | 0 |

Base-case scenario is designed with activated sludge process only to remove BOD only. The effluent TN and TP of the scenario are 25.5 mg/L and 3.96 mg/L respectively.

**Table S9.** Normalized score of the Level 1 plant with id BNR1

| Impact category | Unit | Impact Score per m3 | Impact Score per year | Normalization factor per year* | Normalized score |
|---|---|---|---|---|---|
| Eutrophication | kg N eq | 0.0165 | 228666.67 | 6.60E+09 | 3.46E-05 |
| Carcinogenics | CTUh | 1.64E-08 | 0.226 | 1.16E+05 | 1.95E-06 |
| Non carcinogenics | CTUh | 3.10E-08 | 0.428 | 3.21E+05 | 1.33E-06 |
| Ecotoxicity | CTUe | 0.246 | 3395997.76 | 3.32E+12 | 1.02E-06 |
| Global warming | kg CO2 eq | 0.994 | 15227345.58 | 7.40E+12 | 1.86E-06 |
| Ozone depletion | kg CFC-11 eq | 1.08E-08 | 0.149 | 4.90E+07 | 3.04E-09 |
| Acidification | kg SO2 eq | 0.0016 | 21941.79 | 2.80E+10 | 7.84E-07 |

** Normalization factors are collected from Ryberg et al., which is based on 2008 US inventory data.*[13]

We have estimated the normalized score of all the impact categories for a Level 1 plants with id BNR1 as reported in Table S9. Normalized score is calculated by dividing the impact score by the normalization factors, which are the total impacts in each category in the US based on 2008 inventory data as reported in Ryberg *et al.*[13] These normalized scores allow for comparison of plant-level results across impact categories, relative to US totals.

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