Supplementary Materials

Recovery of Phosphorus from Waste Water Profiting from Biological Nitrogen Treatment: Upstream, Concomitant or Downstream Precipitation Alternatives

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Table S1. Relevant words included (or discarded) in the multi-term topic search assessed via the Web of Science Core Collection (Clarivate Analytics, USA).

<table>
<thead>
<tr>
<th>Topic</th>
<th>Words</th>
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</thead>
<tbody>
<tr>
<td>Core element under study</td>
<td>&quot;ortho-phosphate&quot; OR &quot;orthophosphate&quot; OR &quot;phosphate&quot; OR &quot;phosphorous&quot; OR &quot;phosphorus&quot;</td>
</tr>
<tr>
<td>Management strategy</td>
<td>&quot;<em>recover</em>&quot; OR &quot;recycl*&quot;</td>
</tr>
<tr>
<td>Technological process</td>
<td>&quot;crystal*&quot; OR &quot;formation&quot; OR &quot;<em>minerali</em>&quot; OR &quot;precipit*&quot; OR &quot;production&quot;</td>
</tr>
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<td>Product formed</td>
<td>&quot;apatite*&quot; OR &quot;bobierrite&quot; OR &quot;brushite&quot; OR &quot;monenite&quot; OR &quot;newberyite&quot; OR &quot;struvit*&quot; OR &quot;vivianite&quot;</td>
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<tr>
<td>By-products to be processed</td>
<td>&quot;biosolid*&quot; OR &quot;centrate*&quot; OR &quot;digestate*&quot; OR &quot;dung&quot; OR &quot;effluent*&quot; OR &quot;filtrate*&quot; OR &quot;leachate*&quot; OR &quot;liquor*&quot; OR &quot;manure&quot; OR &quot;residu*&quot; OR &quot;sewage&quot; OR &quot;sludge*&quot; OR &quot;slurr*&quot; OR &quot;stream*&quot; OR &quot;supernatant*&quot; OR &quot;urine&quot; OR &quot;waste*&quot; OR &quot;WWTP*&quot;</td>
</tr>
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| P-related chemicals and compounds | "acetyl phosph*" OR "*adenosin*" OR "*alanin*" OR "arginine phosph*" OR "carbonate apatite*" OR "cellulose phosphate" OR "chloro-phosph*" OR "*dinucleotide*" OR "*fluorophosphoric*" OR "*hypoxanthine*" OR "*ketone*" OR "*lipid-phosphate*" OR "molybdopho*" OR "*monobasic potassium phosphate*" OR "nitrophosphate*" OR "organo-phosph*" OR "organophosph*" OR "pentose phosph*" OR "peptide*" OR "phosphate-buffered*" OR "phosphate buffer*" OR "phosphate cement*" OR "phosphate ceramic*" OR "phosphate group*" OR "phosphate transporter*" OR "*phosphine*" OR "phosphinite*" OR "*phosphate*" OR "*phosphite*" OR
"phosphogypsum" OR "phosphomannos" OR "phosphomolyb" OR "phosphonate" OR "phosphopeptid" OR "phosphoric ester" OR "phosphorite" OR "phosphoryl" OR "phosphoserin" OR "pyridoxal" OR "pyrophosphate" OR "sulphonate" OR "tributyl phosphate" OR "tricresyl phosphate" OR "analgesic" OR "antibiotic" OR "antibody" OR "antigenic" OR "arthritis" OR "blood" OR "bone" OR "calculi" OR "cancer" OR "cartilage" OR "catheter" OR "cisplatin" OR "clampsia" OR "clinical" OR "coronary" OR "cortisol" OR "createine" OR "crystalluria" OR "cystoplast" OR "cytophatic" OR "dental" OR "dentin" OR "disease" OR "disinfect" OR "enamel" OR "endocrine" OR "fetal" OR "heart" OR "hepatitis" OR "holmium" OR "immunoassay" OR "implant" OR "inflammatot" OR "inositol" OR "kidney" OR "kinase" OR "laser-induced damage" OR "lincomycin" OR "lithostatine" OR "liver" OR "loperamide" OR "lung" OR "lysosome" OR "mamall" OR "mammary-gland" OR "mucos" OR "mutagen" OR "nephro" OR "nucleotide" OR "orthopaedic" OR "pericardium" OR "polyoma" OR "precipitation of protein" OR "prostat" OR "protease" OR "renal" OR "salivar" OR "sanniet" OR "synaptic" OR "tendinopathy" OR "testosterone" OR "therap" OR "tooth" OR "urolithiasis" OR "urothelial"

Biomedical studies

"archaeobotany" OR "archaeologist" OR "amphibian" OR "antarctic" OR "boreal" OR "chlorospodioid" OR "diamond" OR "lentic ecosystem" OR "lootic ecosystem" OR "magma" OR "metamorphism" OR "mimetite" OR "paleocen" OR "prehistoric" OR "pollen" OR "pyrite" OR "riparian" OR "silicate" OR "soil structure"

Natural history, ecosystems, mineralogy and other related studies

"actinide" OR "antimony" OR "barium" OR "cesium" OR "erbium" OR "fission" OR "lanthanide" OR "lanthanum" OR "lithium" OR "neodymium" OR "nuclear waste" OR "plutonium" OR "production of HF" OR "radioactive material" OR "radioactive waste" OR "radionuclide" OR "scandium" OR "strontium" OR "technogenic waste" OR "thorium" OR "uranium" OR "vanadium"

Radioactivity and chemical studies

(("4-phosphate" OR "6-phosphate" OR "adsorbent" OR "agricultur" OR "Al and Fe" OR "Al/Fe" OR "Al:Fe" OR "alkanoate" OR "alum" OR "ash" OR "BNR" OR "clogging" OR "coagula" OR "combustion" OR "electrodialy" OR "Fe and Al" OR "fertilizer" OR "floccul" OR "incinerat" OR "ion exchange" OR "iron" OR "membrane" OR "osmosis" OR "P removal" OR "phosphate discharge" OR "phosphate removal" OR "phosphorous discharge" OR "phosphorous discharge" OR "phosphorous removal" OR "phosphorus removal" OR "polyphosphate" OR "removal of phosphate" OR "removal of phosphorous" OR "removal of phosphorus" OR "scale" OR "scaling" OR "soil" OR "sorption" OR "sediment" OR "wetland") NOT ("apatite" OR "bobierrite" OR "brushite" OR "calcite" OR "magnesi" OR "monenite" OR "sorption") OR "phosphogypsum" OR "phosphomannos" OR "phosphomolyb" OR "phosphonate" OR "phosphopeptid" OR "phosphoric ester" OR "phosphorite" OR "phosphoryl" OR "phosphoserin" OR "pyridoxal" OR "pyrophosphate" OR "sulphonate" OR "tributyl phosphate" OR "tricresyl phosphate" OR "analgesic" OR "antibiotic" OR "antibody" OR "antigenic" OR "arthritis" OR "blood" OR "bone" OR "calculi" OR "cancer" OR "cartilage" OR "catheter" OR "cisplatin" OR "clampsia" OR "clinical" OR "coronary" OR "cortisol" OR "createine" OR "crystalluria" OR "cystoplast" OR "cytophatic" OR "dental" OR "dentin" OR "disease" OR "disinfect" OR "enamel" OR "endocrine" OR "fetal" OR "heart" OR "hepatitis" OR "holmium" OR "immunoassay" OR "implant" OR "inflammator" OR "inositol" OR "kidney" OR "kinase" OR "laser-induced damage" OR "lincomycin" OR "lithostatine" OR "liver" OR "loperamide" OR "lung" OR "lysosome" OR "mamall" OR "mammary-gland" OR "mucos" OR "mutagen" OR "nephro" OR "nucleotide" OR "orthopaedic" OR "pericardium" OR "polyoma" OR "precipitation of protein" OR "prostat" OR "protease" OR "renal" OR "salivar" OR "sanniet" OR "synaptic" OR "tendinopathy" OR "testosterone" OR "therap" OR "tooth" OR "urolithiasis" OR "urothelial"

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"newberyite" OR "recover*" OR "*struvite*" OR "vivianite") OR
"alumina recovery" OR "EBPR recovery" OR "phytoremediation" OR
"production of available phosphorus from rock phosphate" OR
"recovered by backwashing" OR "recovering alloy steels" OR
"recovery of normal operation" OR "rhizofiltrat*

"cheese quality" OR "D2EHPA" OR "DBDECMP" OR "flame" OR
"glass-ceramics" OR "LDH" OR "LUKE" OR "parenteral
nutrition" OR "resilon" OR "silicon" OR "thermal ionization" OR
"titanium" OR "u-th-ra" OR "water-ethanol"

Others

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Table S2. Summary of experiences integrating chemical precipitation aiming at P recovery followed by biological N oxidation, or removal (upstream precipitation).

<table>
<thead>
<tr>
<th>Waste water source¹</th>
<th>Precipitation performance ²</th>
<th>Bioprocess performance</th>
<th>Precipitate characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDN as the bioprocess following chemical P precipitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrolysed urine</td>
<td>MgP precipitated in lab tests simultaneously to vacuum thermal stripping (+acid absorption) at 25–65°C using MgCl₂</td>
<td>NDN via nitrite in a continuous-flow AS AO MBR (2.4 L)</td>
<td>Increased COD/N (4.7) and ALK/NH₄⁺-N (4.4) mass ratios after precipitation favoured NDN</td>
<td>MgP mostly precipitated as MAP (&gt;90 wt%) according to XRD and chemical analysis of the solid [68]</td>
</tr>
<tr>
<td>Composition: pH 9.1, ALK 19692, COD 5868, TN 5280, NH₄⁺-N 5193, TP 280, Mg &amp; Ca not detected</td>
<td>3 h batch stripping tests at 60°C and 21.3 kPa → 80% infl. N recovery; solids produced: 25.3 g/L_{urine} [(NH₄)₂SO₄ + NH₄HSO₄: 85.5 + 13.9 wt%] Mg/P adjusted to 1.2/1 → PUE &gt;95%; solids produced: 1.5 g/L_{urine}</td>
<td>NLR 0.37 g N L⁻¹ d⁻¹, NRE &gt;80%; higher efficiency limited by ALK shortage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobically digested sludge dewatering centrate from a municipal WWTP</td>
<td>MgP precipitated in a lab batch reactor (3.5 L) MgCl₂ added, pH 8.5 (NaOH), reaction time 10 min</td>
<td>Nitrification in a fixed-film aerated reactor (0.4 L), denitrification in a MFC-cathode (0.1 L); MFC-anode fed with raw waste water (270 mg COD L⁻¹)</td>
<td>No data available for the precipitate</td>
<td>[105]</td>
</tr>
</tbody>
</table>
### Side-stream sludge fermenter effluent from an EBPR system treating low-strength synthetic waste water

**Composition**
- pH 7.0–8.0
- COD 340
- TN 48
- NH₄⁺-N 23
- PO₄-P 7

**fertiliser**
- [CaH₂PO₄] used as P source
- fermentation increased 15% water-soluble P
- and provided extra bCOD

**MgSO₄ supplied at pH 9.0 (NaOH), reaction time 30 min; process optimisable at pH 9.5**
- 41–50% (up to 55%) NH₄⁺ separated

**Global performance**
- 72% COD, 89% N and 98% P reduction

**CaP precipitated in a SBR at 20ºC**
- Ca(OH)₂ added at pH 10
- PUE >99% (65% influent P recovered)

**Composition of the precipitate**
- 13.8% P

**Fermentation of purged sludge followed by precipitation of released P lead to improved simultaneous P uptake and N removal in the mainstream (NRE 80%)**

**[107]**

### Urine

**Composition**
- pH 6.2–7.9
- TN 4670–7630
- NH₄⁺-N 315–2250
- TP 330–

**PO₄ precipitated in a lab stirred system using RO brine (from a reclaimed WWTP in a thermal power**

**NDN via nitrite in a continuous-flow AS AO MBR (10.4 L); influent COD 2500–4000, TN 1800–3200, mg L⁻¹; HRT 2 d**

**Precipitates produced at different brine/urine mixture ratios (0/1–1/1) with 10–15% P**

**[108]**

### Anaerobic lagoon digester supernatant in a swine farm

**Composition**
- pH 8.1
- COD 266
- TN 607
- NH₄⁺-N 598
- PO₄-P 22
- Mg 31

**MgP precipitated in lab batch tests (in beakers)**
- Raw vs. (organically) fermented superphosphate fertiliser
- [Ca(H₂PO₄)₂] used as P source
- fermentation increased 15% water-soluble P
- and provided extra bCOD

**MgSO₄ supplied at pH 9.0 (NaOH), reaction time 30 min; process optimisable at pH 9.5**
- 41–50% (up to 55%) NH₄⁺ separated

**Global performance**
- 71% (lower if fermented superphosphate not used)

**MgP precipitated mostly as MAP according to XRD and SEM-EDS**

**Effectiveness of the precipitate as fertiliser demonstrated in a pot test (increased crop yield)**

**[106]**

### Effluent with TN 1530 mg L⁻¹

**mW/m² –ref. anodic surface–**

**NDN in a SBR (4.5 L); pH adjusted to 7.0 (influent)**

**COD/TN mass ratio raised (0.4 → 1.8) by adding fermented superphosphate favouring NDN (COD 598, NH₄⁺-N 328, mg L⁻¹)**

**NRE 71% (lower if fermented superphosphate not used)**

**Effectiveness of the precipitate as fertiliser demonstrated in a pot test (increased crop yield)**

**[106]**
654, PO₄-P 283–585, Mg 31–65, Ca 68–128

| Plant) as Me ions source at 20°C | NRE 45% (with internal COD), increased to 92% when using methanol as external COD source |
| Brine/urine mixture adjusted to 1/1 vol., pH 9.0 (with NaOH), reaction time 30 min | Mg in the solid decreased from 7 to 2.5%, and Ca raised from 8 to 25% |
| PUE >90% | Global performance: >90% COD, N and >99% P reduction |

Depending on the amount of brine added (Mg+Ca/P molar ratio 0.2–2.3),

- MgP precipitated in lab batch tests (in beakers) at 20°C
- Mg/NH₄/P₂O₅ adjusted with MgCl₂ + K₂HPO₄, pH increased with NaOH, reaction time 2 min, MgP deposits used as seeding material
- Mg/NH₄/P₂O₅ adjusted to 1.0/1.0/1.0 and pH to 9, 65% NH₄⁺ and 95% P₂O₅ separated

- NDN in a continuous-flow AS A/O system (24 L) (+settler) for treating raw sewage plus MgP precipitation effluent

- Mixing of precipitation effluent with raw sewage decreased COD and N removal efficiency

- MgP precipitated mostly as MAP according to XRD

- Quality of the MgP precipitated potentially compromised by the HM content

| Composition: pH 8.8, COD 2694, TN 2024, NH₄⁺-N 1717, TP 420, PO₄-P 326 | Mg and P₂O₅ supply favoured NH₄⁺ separation; addition of seeding material did not enhance N & P precipitation efficiency (but favoured chemical sludge settling); presence of HMs could negatively affect MAP precipitation

- NLR >0.13 g NH₄⁺-N L⁻¹ d⁻¹ (mixture ratio >1/1 vol.) triggered NO₂⁻ accumulation (hypothesised by nitrification inhibition)

| Urine-seawater mixture | Nitrification in a continuously aerated SBR (for subsequent in-

- MgP precipitated mostly as MAP according to XRD and chemical

- [109]
### Low-strength synthetic waste water: Composition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.4–8.0</td>
</tr>
<tr>
<td>COD</td>
<td>250–350 mg/L</td>
</tr>
<tr>
<td>NH₄⁺-N</td>
<td>30–45 mg/L</td>
</tr>
<tr>
<td>PO₄³⁻-P</td>
<td>5–15 mg/L</td>
</tr>
</tbody>
</table>

### CaP precipitation

- CaP precipitated in a lab up-flow reactor at 20°C
- EBPR in a continuous-flow AS A/O system for N & P removal (~300 L)

### Membrane fouling

- Membrane fouling was mitigated when the FBR-MBR system run at optimal conditions

### MgP precipitation

- MgP precipitated in a lab FBR (9.5 L) at 20°C
- P-recovery in FBR enhanced SND and COD, NH₄⁺ and PO₄³⁻ removal in MBR (NRE 99%, PUE 93% at pH 9, HRT 6 h and aeration on/off)

### Membrane fouling

- Membrane fouling was mitigated when the FBR-MBR system run at optimal conditions

### MgP precipitate

- MgP precipitate mostly as MAP according to XRD and SEM-EDS

### CaP precipitate

- CaP precipitate mostly as HAP (or precursors) according to XRD and SEM-EDS

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### Low-strength synthetic waste water: Composition

- COD 250–300 mg/L
- NH₄⁺-N 30–45 mg/L
- PO₄³⁻-P 5–15 mg/L

### CaCl₂ added after the anaerobic stage

- Chemical P precipitation

### Composition of the precipitate

- Composition of the precipitate: 8–13% P
by aeration (5% NH₃ loss), calcite used as seeding material favoured EBPR (PUE > 99%) regardless COD/P mass ratio (20–67); final effluent with <1 mg PO₄-P/L COD and NH₄⁺ removal efficiency as 84–87% regardless COD/P mass ratio

Precipitate with Ca/P molar ratio >1.67 due to carbonate co-precipitation; high P release in the anaerobic stage favoured HAP crystallisation

EBPR in a SBR alternating AO phases also involved partial N removal through NDN (NRE 25%)

Fermentation of purged sludge followed by precipitation of the released N and P, plus reintroduction of VFAs formed into EBPR system, lead to higher P separation efficiency (P in the effluent reduced by >65%) and complete nitrification

MgP precipitate mostly as MAP according to supernatant analysis and XRD

MgP precipitate partly as MAP according to XRD and EDS

Anhydrous precipitate with 25.3% P, 18.3% Mg, 7.1% N, 5.4% K, 2.5% Ca

Quality of the precipitate potentially compromised by the organic content (35 wt% as COD)
78–92% NH₄⁺, 84–93% PO₄ (besides 74% TSS, 47% COD) separated

- 50 to 267–430 favouring EBPR
- MgP precipitation enhanced nitrification and ARE due to a reduced OLR and NLR once fixed HRT, low NH₃ levels in bioreactors (eventually toxic triggering NO₂- accumulation)

- OLR 4.5 g COD L⁻¹ d⁻¹, NLR 0.18 g N L⁻¹ d⁻¹ → NRE >90% (NH₄⁺)

### Anaerobically digested landfill leachate

| Composition: pH 7.5–8.1, ALK 11120, Cl⁻ 2000, COD 12000, BOD₄ 4250, NH₄⁻-N 2800, TP 14 | BOD₅/NH₄⁻-N mass ratio increased from 1.5 to 6.5 favouring NDN, 6-fold Cl⁻ raise (12 g L⁻¹) | MgP precipitated in a lab stirred system using MgCl₂ and PO₄, Mg/NH₄/Po₄ adjusted to 0.7/1.0/0.7, pH 9, reaction time 2 h, 70% NH₄⁺ separated | The higher MgCl₂ addition the higher NH₄⁺ separation as MAP, but Cl⁻ >12 g L⁻¹ limited nitrification (triggering NH₄⁺ accumulation in the bioreactor) |

### Rare-earth smelting waste water

| Composition: pH 0.77, COD 1088, NH₄⁻-N 1540, La³⁺ 200, Eu³⁺ 78 | MgP precipitate mostly assumed as MAP. Composition: 15.6% P, 9.3% N, 8.3% Mg | MgP precipitated in lab batch tests (in beakers) at 20°C | COD/NH₄⁻-N mass ratio increased from 0.7 to 7.2 favouring NDN (COD 566, NH₄⁻-N 79, mg L⁻¹) | Quality of the MgP precipitated compromised by the rare metal content |

### MgP precipitated in a lab stirred system using MgCl₂ and PO₄, Mg/NH₄/Po₄ adjusted to 0.7/1.0/0.7, pH 9, reaction time 2 h, 70% NH₄⁺ separated

- BOD₅/NH₄⁻-N mass ratio increased from 1.5 to 6.5 favouring NDN, 6-fold Cl⁻ raise (12 g L⁻¹) | The higher MgCl₂ addition the higher NH₄⁺ separation as MAP, but Cl⁻ >12 g L⁻¹ limited nitrification (triggering NH₄⁺ accumulation in the bioreactor) |

### MgP precipitated in lab batch tests (in beakers) at 20°C

- COD/NH₄⁻-N mass ratio increased from 0.7 to 7.2 favouring NDN (COD 566, NH₄⁻-N 79, mg L⁻¹) | Quality of the MgP precipitated compromised by the rare metal content |

### MgP precipitated in a lab batch tests (in beakers) at 20°C

- MgP precipitate mostly assumed as MAP. Composition: 15.6% P, 9.3% N, 8.3% Mg | Quality of the MgP precipitated compromised by the rare metal content |

### MgP precipitated in a lab batch tests (in beakers) at 20°C

- MgP precipitate mostly assumed as MAP. Composition: 15.6% P, 9.3% N, 8.3% Mg | Quality of the MgP precipitated compromised by the rare metal content |
<table>
<thead>
<tr>
<th>Process Description</th>
<th>Removed Components</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg/NH₄/PO₄ adjusted to 1.2/1.0/1.3, pH 11.1–11.2, reaction time 1.5 h</td>
<td>Rare metal ions removed from the liquid phase</td>
<td>When Ca dosed instead of Mg, CaP formed hypothesised as Ca-struvite. Composition: 18.3% Ca, 13.6% P, 6.5% N</td>
</tr>
<tr>
<td>95% NH₄⁺ separated</td>
<td>NLR 0.13 g NH₄⁺-N L⁻¹ d⁻¹, NRE 86% (NH₄⁺)</td>
<td></td>
</tr>
<tr>
<td>Using CaO (not KOH) and Ca₃(PO₄)₂ (not MgSO₄, Na₂HPO₄) → ~80% NH₄⁺ separated</td>
<td>NDN in a fill-and-draw system under intermittent aeration (air on/off 1/1 h)</td>
<td></td>
</tr>
<tr>
<td>MgP precipitated in lab batch tests (in beakers)</td>
<td>BOD/TN increased from 1.6 to 7 enhancing NDN (BOD 8200, TN 1166, mg L⁻¹)</td>
<td>Composition of the MgP not determined analytically [66,118]</td>
</tr>
<tr>
<td>Raw swine waste water obtained by centrifugation</td>
<td>NLR 0.97 g N L⁻¹ d⁻¹, NRE improved from 55% to 88% when PO₄ was decreased</td>
<td></td>
</tr>
<tr>
<td>Composition: pH 8.5, BOD 9500, TN 5930, NH₄⁺-N 2500, TP 360, PO₄-P 302</td>
<td>Additional 60% PO₄ precipitated as CaP by adding CaCl₂ once biotreatment ended</td>
<td></td>
</tr>
<tr>
<td>Mg/NH₄/PO₄ adjusted with MgCl₂ + KH₂PO₄, pH increased with NaOH</td>
<td>Composition of the MgP not determined analytically [66,118]</td>
<td></td>
</tr>
<tr>
<td>Mg/NH₄/PO₄ adjusted to 0.9/1.0/0.6, pH 7.5, temperature 25°C, reaction time 1 h</td>
<td>NLR 0.97 g N L⁻¹ d⁻¹, NRE improved from 55% to 88% when PO₄ was decreased</td>
<td></td>
</tr>
<tr>
<td>79–87% NH₄⁺, 40–88% P separated</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PNA as the bioprocess following chemical P precipitation**

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Removed Components</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digester sludge thickening lagoon supernatant in a municipal WWTP</td>
<td>PNA in a IFAS-SBR (6 L) with intermittent aeration</td>
<td>PNA in a IFAS-SBR (6 L) with intermittent aeration</td>
</tr>
<tr>
<td>Composition: pH 8.0, ALK 3180, TSS 344,</td>
<td>NLR 0.31 g N L⁻¹ d⁻¹, NRE improved from 55% to 88% when PO₄ was decreased</td>
<td>No data available for the precipitate [69]</td>
</tr>
<tr>
<td>COD 644, NH₄⁺-N 892, PO₄-P 235</td>
<td>High PO₄ inhibited anammox bacteria, higher tolerance to PO₄ stress when biomass grew as biofilm rather than forming flocs</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Anaerobically digested sludge dewatering centrate in a municipal WWTP</strong></td>
<td><strong>MgP precipitated in a lab CSTR (10 L) at 10°C with MgO</strong></td>
<td>PNA as 2-step process (PO₄ precipitated after PN) and also as 1-step process (with intermittent aeration) using SBRs (3.5 L)</td>
</tr>
<tr>
<td>Composition: pH 8.0–8.8, TIC 681–893, COD 410–510, NH₄⁺-N 1081–1177, PO₄-P 260–351</td>
<td>Mg/P adjusted to 1, reaction time 2.5 h; PO₄-P reduced to 31 mg L⁻¹</td>
<td>Composition of the MgP formed not determined analytically [119]</td>
</tr>
<tr>
<td>MgP formation (incl. eventual NH₃ stripping) resulted in 8% NH₄⁺ separation</td>
<td>NRR ~0.3 g N L⁻¹ d⁻¹ for both configurations</td>
<td>45–50% anammox activity drop at ~300 mg P L⁻¹</td>
</tr>
<tr>
<td>lower sensitivity to PO₄-P was estimated in short-term experiments (IC₅₀: 650 mg L⁻¹ at 35°C, pH 6.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Anaerobically digested industrial (potato) waste water</strong></td>
<td><strong>MgP precipitated in a lab mixed reactor (4 L) with MgCl₂</strong></td>
<td>PNA as 2-step process (20 L CSTR w/o sludge retention + 3.7 L UFBR) and also as 1-step process (UFBR) at 35°C</td>
</tr>
<tr>
<td>Composition (anaerobic effluent 2-fold diluted): pH 7.9, TIC 396, NH₄⁺-N 203, PO₄-P 57, Mg 39</td>
<td>pH adjusted to 7.8 (NaOH)</td>
<td>NLR 0.1–0.25 g N L⁻¹ d⁻¹</td>
</tr>
<tr>
<td>Urea (1.5%) added to the crystallisator as N source (in presence of anaerobic sludge), HRT 6–7 h</td>
<td>MgP precipitate mostly as MAP according to XRD [120]</td>
<td>Global performance (2-step process): 86% N, 83% PO₄ reduced</td>
</tr>
<tr>
<td>Anaerobically digested industrial (potato) waste water from a UASB reactor + anaerobically digested sludge dewatering centrate in a municipal WWTP</td>
<td>MAP precipitated by the PHOSPAQ™ process at full-scale (2*500 m³), aeration supplied for bCOD degradation and CO₂ stripping</td>
<td>MAP with low HM content with respect to EU standards for fertilisers</td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>Composition: COD 565, NH₄⁺-N 372, PO₄-P 73</td>
<td>MgO dosed and pH adjusted to 8.2–8.3; PUE ~67% (feasible &gt;80%)</td>
<td>Precipitate fertilising effectiveness demonstrated in field tests (= performance as commercial fertilisers)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[121–122]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anaerobically co-digested sludge dewatering supernatant in a municipal WWTP</th>
<th>MgP precipitated in a CSTR (50 L) using MgCl₂ or MgCO₃</th>
<th>PNA as 2-step process: MBBR (7.4 L) + SBR (30 L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition: NH₄⁺-N 651, PO₄-P 73</td>
<td>Solids &gt;0.8 mm removed before precipitation</td>
<td>PN: NLR 1 g N L⁻¹ d⁻¹, NCE 50% (at 30°C)</td>
</tr>
<tr>
<td></td>
<td>Mg/P adjusted to 1.3, reaction time 24 h; PO₄-P reduced to 18 mg L⁻¹</td>
<td>Anammox: PO₄-P increase from 30 to 55 mg L⁻¹ implied SAA loss of 45% (in 7 days); by decreasing PO₄-P to &lt;20 mg L⁻¹ activity was recovered (SAA ≤100 mg N₂ g⁻¹ VSS d⁻¹, at 35°C); anammox activity was potentially limited at pH 7 and TIC &lt;24 mg L⁻¹</td>
</tr>
<tr>
<td></td>
<td>MgP formation (incl. eventual NH₃ stripping) resulted in 4.5% NH₄⁺ separation</td>
<td>Composition of the MgP formed not determined analytically</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[67]</td>
</tr>
</tbody>
</table>

Abbreviations: A²O, anaerobic-anoxic-oxic; ALK, alkalinity (as CaCO₃); anammox, anaerobic ammonium oxidation; AO, anaerobic-oxic; AS, activated sludge; BOD, biochemical oxygen demand; CaP, calcium phosphate; COD, chemical oxygen demand (b-, biodegradable; s-, soluble); CSTR, continuous stirred tank reactor; EBPR, enhanced biological P removal; EDS, energy dispersive X-ray spectroscopy; FBR, fluidised bed reactor; HM, heavy metal; HRT, hydraulic residence time; IC₅₀, half maximal inhibitory concentration; IFAS, integrated fixed film AS; MAP, magnesium ammonium phosphate; MBR, membrane bioreactor; MBBR, moving bed bioreactor; Me, metal; MFC, microbial fuel cell; MgP, magnesium phosphate; N, nitrogen; NCE, N conversion efficiency; NLR, N loading rate; NDN, nitrification-denitrification; NRE, N removal efficiency; NRR, N removal rate; OLR, organic loading rate; P, phosphorus; PNA, partial nitritation-anammox; PUE, P uptake efficiency; RO, reverse osmosis; SAA, specific anammox activity; SBR, sequencing batch reactor; SEM, scanning electron microscope; SND, simultaneous NDN; TIC, total inorganic carbon; TN, total N; TP, total P; TSS, total suspended solids; UASB, upflow anaerobic sludge blanket; UFBR, upflow fixed bed reactor;
VFA, volatile fatty acids; VSS, volatile suspended solids; WWTP, waste water treatment plant; XRD, X-ray diffraction.

1 Composition, concentrations expressed in mg L⁻¹.
2 Ca/P, Mg/P and other component ratios expressed in molar units.

**Table S3.** Summary of experiences integrating biological N oxidation, or removal, and mineral precipitation aiming at P recovery inside the bioreactor (concomitant precipitation).

<table>
<thead>
<tr>
<th>Waste water source ¹</th>
<th>Experimental conditions</th>
<th>Bioprocess performance</th>
<th>Precipitate characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrification as the bioprocess concomitant to P precipitation</td>
<td>Long-term nitrification in trickling filters (6 L) partially packed with pumice &amp; mussel shells (CaCO₃ content: ~75 vol%)</td>
<td>PO₄ precipitation induced by Ca released from mussel shells</td>
<td>Composition of the CaP formed not determined analytically</td>
<td>[168]</td>
</tr>
<tr>
<td>Synthetic urine</td>
<td>Process at 29°C considering urine solutions at different concentrations</td>
<td>Mussel shells also provided carbonate needed for buffering the system (the higher the concentration of urine the higher the CaP formed and the buffering capacity released)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition: TN 7780, NH₄-N 400, PO₄-P 890</td>
<td>Urine concentration did not influence filter performance in terms of stability and nitrate production rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic waste water mimicking anaerobic digester dewatering centrate</td>
<td>PN in aerated SBR (10 L) vs. SBBR (16 L) packed with polyethylene particles</td>
<td>SBR: NLR 0.19 g NH₄-N L⁻¹ d⁻¹ and NCE 95%, PLR 0.04 g PO₄-P L⁻¹ d⁻¹ and PUE 40–90% (depending on NH₄⁺ availability within the reactor), faster start-up</td>
<td>Mineral crystals identified in the sludge when observed at the microscopy</td>
<td>[71]</td>
</tr>
<tr>
<td>Composition: HCO₃⁻ 4700, COD 480, NH₄-N 470-590, PO₄-P 100, Mg 45, Ca 115</td>
<td>Process at 30°C and pH 7.5</td>
<td>SBBR: NLR 0.35 g NH₄-N L⁻¹ d⁻¹ and NCE 40%, PLR 0.07 g PO₄-P L⁻¹ d⁻¹ and PUE 70%, more stable facing disturbances in</td>
<td>Suspended solids containing 9–10% P</td>
<td></td>
</tr>
</tbody>
</table>

Mineral crystals identified in the sludge when observed at the microscopy.

Suspended solids containing 9–10% P.

Complementary work in the SBR transforming PN into NDN [169] showed (using XRD) that PO₄ precipitated in different form depending on pH (7–8.5): mainly as HAP at...
<table>
<thead>
<tr>
<th>dissolved oxygen conditions</th>
<th>pH &gt; 7.5 and partly as MAP (potentially associated to CaCO₃) at pH &gt; 8.0</th>
</tr>
</thead>
</table>

**Anammox as the bioprocess concomitant to P precipitation**

<table>
<thead>
<tr>
<th>Synthetic waste water mimicking effluent from a PN reactor</th>
<th>Anammox process in an EBR with internal recirculation</th>
<th>CaP recovered as HAP according to chemical analysis of the solid formed (Ca/P molar ratio 1.67)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition: pH 7.4, TIC 71, NH₄⁺-N 135, NO₂⁻-N 178, PO₄⁻-P 13, Ca 85</td>
<td>Reactor (5 L) at 33°C and pH 8.6 with 43.9–70.3 g VSS L⁻¹ (17% of the TSS)</td>
<td>Granules with 83% mineral content, 28.9% Ca, 13.4% P, 0.9% N, 0.5% Mg</td>
</tr>
</tbody>
</table>

| NLR 5 g NH₄⁺-N L⁻¹ d⁻¹ and NRE 87%; PLR 0.21 g PO₄⁻-P L⁻¹ d⁻¹ and PUE 66%; Granule size 1.3–1.7 mm | Complementary work [170] in an attached film EBR (35°C) reached NLR 50 g NH₄⁺-N L⁻¹ d⁻¹ and NRE 90% + PLR 0.55 g PO₄⁻-P L⁻¹ d⁻¹ and PUE 72% | The core of the granule contained more Ca than the external part (30% vs. 27%) probably due to the formation of CaCO₃ or type-B carbonate apatite |

**PNA as the bioprocess concomitant to P precipitation**

<table>
<thead>
<tr>
<th>Anaerobically digested sludge dewatering centrate in a municipal WWTP</th>
<th>PNA process as 1-stage SBR (10 L) at 25°C and pH ~7.2 with 1.45 g VSS L⁻¹ (62% of the TSS)</th>
<th>CaP recovered as HAP according to XRD and chemical analysis of the solid formed (Ca/P molar ratio 1.64)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLR 0.31 g NH₄⁺-N L⁻¹ d⁻¹ and NRE 66%</td>
<td>Complementary work [171] in an attached film EBR (35°C) reached NLR 10 g NH₄⁺-N L⁻¹ d⁻¹ and NRE 77% + PLR 0.15 g PO₄⁻-P L⁻¹ d⁻¹ and PUE 68% (CaCl₂ added in recirculation)</td>
<td>Granules purged with 71% mineral content,</td>
</tr>
</tbody>
</table>

CaP recovered as HAP according to chemical analysis of the solid formed (Ca/P molar ratio 1.67)

Granules with 83% mineral content, 28.9% Ca, 13.4% P, 0.9% N, 0.5% Mg

The core of the granule contained more Ca than the external part (30% vs. 27%) probably due to the formation of CaCO₃ or type-B carbonate apatite

Granules purged with 71% mineral content,
### Composition:

| pH 8.1, ALK 4401, NH₄⁺-N 966, PO₄-P 57, Ca 79, Mg 14 | No addition of chemicals (w/o pH control) | 33.5% Ca, 15.8% P, 0.2% Mg |

*HMs content complied with EU standards for P fertilisers and requirements from P industry.*

### Abbreviations:

- ALK: alkalinity (as CaCO₃)
- anammox: anaerobic ammonium oxidation
- COD: chemical oxygen demand
- EBR: expanded bed reactor
- HAP: hydroxyapatite
- HM: heavy metal
- N: nitrogen
- NCE: N conversion efficiency
- NLR: N loading rate
- NRE: N removal efficiency
- P: phosphorus
- PLR: P loading rate
- PN: partial nitritation
- PN-anammox: PUA
- PUE: P uptake efficiency
- SBBR: sequencing batch biofilm reactor
- SBR: sequencing batch reactor
- SRT: solids retention time
- TIC: total inorganic carbon
- TSS: total suspended solids
- VSS: volatile suspended solids
- WWTP: waste water treatment plant
- XRD: X-ray diffraction

### Table S4.

Summary of experiences integrating biological N oxidation, or removal, followed by chemical precipitation aiming at P recovery (downstream precipitation).

<table>
<thead>
<tr>
<th>Waste water source</th>
<th>Bioprocess performance</th>
<th>Precipitation performance</th>
<th>Precipitate characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nitrification as the bioprocess preceding chemical P precipitation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobically digested swine waste water from a UASB reactor</td>
<td>Nitrification in a continuous aerated system at pilot-scale</td>
<td>CaP precipitated in lab batch tests (in beakers) using hydrated lime [10% Ca(OH)₂]</td>
<td>Field tests under equivalent conditions also performed; sludge formed contained 30.0% Ca, 5.7% P, 2.5% Mg; the high Ca/P ratio (~4.6) indicated co-precipitation</td>
<td>[74]</td>
</tr>
<tr>
<td>Composition: pH 7.6 (7.0), ALK 3231 (428), TOC 636 (154), NH₄⁺-N 882 (160), PO₄-P 33 (98), s-Ca 98 (204)</td>
<td>Similar tests also conducted considering NDN and PNA as the bioprocess preceding P precipitation (less satisfactory results obtained according to PUE and Ca/P ratio); as far as ALK availability increased P content in precipitate decreased</td>
<td>Lime injected under stirring up to pH 9 (24 h settling); PUE &gt;90% (PO₄) with Ca/P 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobically digested industrial (potato) waste water from a UASB reactor</td>
<td>Nitrification in an aerated CSTR (3.6 L + settler) with NCR 0.26 g NH₄⁺-N L⁻¹ d⁻¹</td>
<td>CaP precipitated in a lab CSTR (3.6 L + settler) with CaCl₂; pH 7.8–10.5 and Ca/P 0.7–1.5; tests at room temperature</td>
<td>CaP precipitated mostly as HAP according to XRD and chemical analysis of the solid formed</td>
<td>[206]</td>
</tr>
<tr>
<td>Composition: pH 8.1 (7.9), TIC 587 (77), NH₄-N 293 (9), NO₃-N 0 (304), PO₄-P 50 (55), Mg 30 (29), Ca 47 (46), K 1213 (1239)</td>
<td>PUE 70% PO₄ at pH 7.8 with CaP yield depending on Ca ions availability; high pH and Ca/P initiated co-precipitation of carbonates and MgP</td>
<td></td>
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<tr>
<td>---------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>PUE 70% PO₄ at pH 7.8 with CaP yield depending on Ca ions availability; high pH and Ca/P initiated co-precipitation of carbonates and MgP</td>
<td>Composition: Ca/P/Mg ratio as 1.5/1.0/0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrification reduced Ca(HCO₃)₂ inhibition and carbonate precipitation making Ca available for CaP precipitation</td>
<td>CaP precipitated in lab batch tests (in beakers), 1 h reaction time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca/P molar ratio increased from 2.6 to 4.8 (66% PO₄ reduction)</td>
<td>Several chemicals used (NaOH, Ca(OH)₂, Na₂CO₃) to raise pH (8.5–9.0) and test effect of TIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg content and pH increased due to preliminary ureolytic phosphate removal</td>
<td>TIC decrease due to nitrification (&gt;90%) implied shorter dosage of NaOH for raising the pH; NaOH supply w/o nitrification may lead to MgP &amp; CaCO₃ formation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrification in an aerated MBR (25 L)</td>
<td>pH increase with Ca(OH)₂: favoured PO₄ precipitation due to extra Ca dosage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg content and pH increased due to preliminary ureolytic phosphate removal</td>
<td>pH increase with Na₂CO₃ hampered Ca and PO₄ precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition of the precipitate not determined analytically</td>
<td>Similar results than in [207] where P uptake was assessed as a function of reaction time, pH, Ca/P and presence of competitive ions; optimal TIC/NH₄⁺ molar ratio before nitrification ~2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Surface lagoon liquids from swine farms

Composition:
P\text{H} 7.9–8.6 (6.0–7.5), ALK 953–3618 (20–156), NH\text{4}^{+}-N 100–723 (0–79), NO\text{3}--N 0–20 (100–523), TP 26–85 (26–85), Mg 6–252, Ca 24–123, K 269–949

- Nitrification in fluidised bed reactors (1.2 L) with sludge immobilised in supporting porous medium (3–5 mm cubes) at 30°C with NCR 0.26 g NH\text{4}^{+}-N L\text{\textsuperscript{-1}} d\text{\textsuperscript{-1}}
- pH 6–12 and Ca/P 1–10 tested; Ca(OH)\text{\textsubscript{2}} added as precipitant (hydrated lime suspended in water)
- pH increased to ≥9.5 for optimum P precipitation; PUE >90% TP
- Similar field test in [73] (reactor vol. 379 L, hydrated lime injected after nitrification until pH 9.0–10.5); P in effluent adjustable for on-farm use according to crop needs (N/P ratio)
- >90% ALK reduction and prevention of NH\text{3} emission

NDN as the bioprocess preceding chemical P precipitation

- MgP precipitated in a continuous pilot-scale unit (320 L + settler); NLR 48–72 g N L\text{\textsuperscript{-1}} d\text{\textsuperscript{-1}}
- Mg/NH\text{4}/PO\text{\textsubscript{4}} adjusted to 1.5–1.8/1.0/1.5–1.8 with MgCl\text{\textsubscript{2}} + H\text{3}PO\text{\textsubscript{4}}; pH 11–12 (NaOH)
- Mg and PO\text{\textsubscript{4}} recovered from the precipitate by heating (while NH\text{3} stripped out) allowing the recycling within the process (>90 wt%)

Fertiliser industry waste water

Composition: TN 350, NH\text{4}--N 245, NO\text{3}--N 21

- NDN in a continuous flow AS AO system at pilot-scale (760 L); NLR 0.6–1.3 g N L\text{\textsuperscript{-1}} d\text{\textsuperscript{-1}}; nitrification partially inhibited; denitrification achieved by adding methanol
- Composition of the precipitate after drying: 24.0% P, 16.6% Mg, 1.1% N
Residual \( \text{PO}_4 \) removed from the water line electrochemically

Global performance: 88% TN, 87% NH\(_4\)\(^+\), 92% NO\(_3\)\(^-\) reduction

Subfloor slurry from a pig farm, liquid separated by a rotary press

Composition:
- pH 7.8 (8.0), ALK 5469 (1422), TSS 1254 (227), NH\(_4\)\(^-\)N 1213 (124), NO\(_3\)\(^-\)N 0 (221), PO\(_4\)\(^-\)P 82 (76), Mg 44 (16), Ca 106 (39), K 1551 (1420)

NDN in a continuous flow AS AO system at full-scale (504-m\(^3\))
- Influent waste water with Ca/P molar ratio 0.4
- 74% ALK, 87% COD, 90% NH\(_4\)\(^+\), 7% PO\(_4\)\(^-\) reduction

CaP precipitated in a continuous full-scale unit, well-mixed and with conical bottom (300 L); hydrated lime [12% Ca(OH)\(_2\)] injected to pH 9.5

PUE 75% PO\(_4\) Composition of the precipitate not determined analytically

0.67 and 0.39 \( \log_{10} \) reductions for total faecal coliforms and enterococci, respectively

NDN in a continuous flow NDN (504 m\(^3\))

MPP precipitated in:
- (1) lab experiments lasting 2–3 h at room temperature
- (2) pilot plant running as CSTR (2-m\(^3\) + settler); MgO added as Mg source; reaction time 0.5 h; TSS may interfere if >1 g L\(^{-1}\)
- (3) full-scale plant (3 CSTRs + settler); MgO added as Mg source achieving <30 mg P L\(^{-1}\) in the effluent

\( Lab: \) Fine-grained elongated crystals with a maximum diameter of several tens of microns

\( Pilot-plant: \) the recovered product contained 12.5% P, 10.7% Mg, 11.4% K, 1.3% Ca, 0.7% N (5.5% organic-C)

Calf manure NDN running at full-scale

MPP precipitated in:
- (1) lab experiments lasting 2–3 h at room temperature
- (2) pilot plant running as CSTR (2-m\(^3\) + settler); MgO added as Mg source; reaction time 0.5 h; TSS may interfere if >1 g L\(^{-1}\)
- (3) full-scale plant (3 CSTRs + settler); MgO added as Mg source achieving <30 mg P L\(^{-1}\) in the effluent

\( Lab: \) Fine-grained elongated crystals with a maximum diameter of several tens of microns

\( Pilot-plant: \) the recovered product contained 12.5% P, 10.7% Mg, 11.4% K, 1.3% Ca, 0.7% N (5.5% organic-C)

**PNA as the bioprocess preceding chemical P precipitation**

Anaerobically digested sludge dewatering centrate from two municipal WWTPs — with chemical vs.

- PNA as 1-step process at lab- (10 L) and pilot-scale
- Centrate with 59 (chemical) vs.

MgP precipitated in lab batch tests (in beakers)
- pH 8–12 (adjusted with NaOH), Mg/P 0.75–1.75, (adjusted

MgP precipitated as MAP & MPP according to XRD and chemical analysis

At pH 11, precipitate composition: 11.4% P,
### Biological P removal in the mainstream

**Composition:**
- pH 7.8–8.0 (7.5–7.7), ALK 3276–3407 (327–752), NH₄⁺-N 949–963 (109–228), PO₄-P 59–222 (53–233), Mg 4–12 (4–14), Ca 21–54 (21–33), K 251–327 (261–367)

**K uptake from water line**
- Ca. 90% ALK, 85% NH₄⁺ reduction

**MgP precipitated in lab batch tests (in beakers) targeting MPP recovery**
- MgP precipitated mostly as MPP with co-precipitation of other salts according to XRD

**High dilution (90%) favoured co-precipitation of Mg₃(PO₄)₂ and Mg(OH)₂; low dilution (0–50%) favoured recovery of all PO₄ as MPP, but with co-precipitation of Mg(OH)₂**

**Up to 80% PO₄ recovery at pH 10 and 90% dilution**

**MgP precipitated mostly as MPP with co-precipitation of other salts according to XRD**

### Anaerobically digested manure centrate

**Composition:**
- TSS (500), NH₂⁻-N (8), PO₄-P (108), Mg (163), Ca (36), K (609)

**After biological treatment, Mg/K/P molar ratio adjusted to ca. 2.0/4.5/1.0**

**Different dilutions rates (0–90%) tested to decrease interference by TSS (K and PO₄ adjusted using chemicals); pH 9–12, 38ºC**

**Up to 80% PO₄ recovery at pH 10 and 90% dilution**

**Suspended particles acted as nuclei for heterogeneous nucleation favouring aggregation of crystals as star-asterisk forms**

**Abbreviations:**
- ALK, alkalinity (as CaCO₃); anammox, anaerobic ammonium oxidation; AO, anoxic-oxic; AS, activated sludge; CaP, calcium phosphate; CSTR, continuous stirred tank reactor; HAP, hydroxyapatite; MAP, magnesium ammonium phosphate; MBR, membrane bioreactor; MgP, magnesium phosphate; MPP, magnesium potassium phosphate; N, nitrogen; NCR, N conversion rate; NDN, nitrification-denitrification; P, phosphorus; PNA, partial nitritation-anammox; PUE: P uptake efficiency; TIC, total inorganic carbon; TOC, total organic carbon; TP, total P; TSS, total suspended solids; UASB, upflow anaerobic sludge blanket; WWTP, waste water treatment plant; XRD, X-ray diffraction.

1 Composition, concentrations expressed in mg L⁻¹; values after biological N treatment in brackets.
2 Ca/P, Mg/P and other component ratios expressed in molar units.