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Energy Neutrality and Nutrient Recovery through ANAMMOX Pretreatment for Potable Reuse: A Transferable Technical Protocol from the Netherlands to Peru

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Abstract

The transition toward energy-neutral, nutrient-recovering water treatment plants is a priority for water-stressed cities. In the Netherlands, integrating A-stage/B-stage configurations, anaerobic ammonium oxidation (ANAMMOX) within the pretreatment line, phosphorus recovery as struvite, and anaerobic digestion has allowed water authorities to move toward energy self-sufficiency and direct-reuse schemes. This article synthesises, through a technical-transfer protocol grounded in verifiable, DOI-documented evidence, the quantitative parameters of these configurations (aeration savings, footprint reduction, biogas production, struvite recovery, and pathogen log-reduction frameworks), contrasting them with a conventional nitrification–denitrification/chlorination configuration. Building on this synthesis, an experimental design adapted to Peruvian conditions is proposed, including construction procedures, analytical chemical assays, a five-stage potabilisation verification protocol aligned with national regulation (Supreme Decree No. 031-2010-SA), and an assessment of SEDAPAL's institutional capacity to adopt this technology, grounded in recent empirical evidence on the determinants of reuse-technology adoption in Peru. Methodological limitations of this technical-comparative, non-primary-experimental study are discussed, and the steps required for a field pilot validation are identified.

1. Introduction

1.1 Background and rationale

The conventional wastewater treatment paradigm, based on nitrification–denitrification with intensive aeration and external carbon dosing, is energy intensive and does not recover the nutrients contained in wastewater. Facing the combined water and energy scarcity many cities confront, research conducted primarily in the Netherlands has shown that it is technically feasible to transform treatment plants into net producers of energy and resources [1, 3]. Anaerobic ammonium oxidation (ANAMMOX), discovered and characterised in sequencing batch reactors by Strous et al. [1] and coupled with partial nitritation (the PN/ANAMMOX or deammonification process), allows nitrogen removal without external organic carbon and with substantially lower aeration demand than conventional nitrification–denitrification [2, 6].

In parallel, the Dutch water authorities' Energy & Raw Materials Factory has demonstrated, at full operational scale, the feasibility of recovering biogas, phosphorus (as struvite), and alginate-like polymers from treatment sludge, covering up to 40% of the sector's energy consumption and generating annual revenues on the order of €24 million from biogas sales [8]. Aerobic granular sludge technology (Nereda) has demonstrated energy reductions of up to 50% and footprint reductions of up to 70% compared with conventional activated sludge [8].

1.2 Knowledge gap and contribution

Although robust pilot- and full-scale evidence exists for mainstream PN/ANAMMOX in temperate European climates [3, 4, 5, 6] and for nutrient recovery [8, 9, 10], the literature does not offer explicit technical protocols for transferring these configurations to Andean-coastal contexts such as Peru, where warmer wastewater temperatures (potentially favourable for ANAMMOX kinetics), heterogeneous sanitation infrastructure, and a fragmented regulatory institutional landscape coexist [15]. To the extent verifiable in indexed databases, no study simultaneously integrates: (i) a quantitative comparison matrix of DOI-documented parameters; (ii) a construction and analytical protocol adapted to Peruvian drinking-water regulation; and (iii) an assessment of the institutional adoption capacity of the country's largest utility (SEDAPAL), grounded in recent empirical evidence on the organisational and institutional determinants of reuse-technology adoption in Peru [15].

This manuscript's contribution is therefore twofold: (a) it synthesises and systematises — without generating new primary experimental data at this stage — the quantitative evidence available on ANAMMOX/nutrient-recovery configurations in the Netherlands, avoiding any unverifiable citation; and (b) it translates that evidence into a technical-transfer protocol, with tools, materials, construction procedures, and specific chemical assays, evaluated against the documented institutional capacity of SEDAPAL.

1.3 Objectives

1) Systematise DOI-documented pilot and operational evidence on PN/ANAMMOX and energy/nutrient recovery in the Netherlands. 2) Propose a technical design and construction procedures for a demonstration plant in Peru with direct reuse. 3) Specify chemical assays, analytical quality control, and a potabilisation verification protocol adapted to Peruvian regulation. 4) Assess, based on published empirical evidence, SEDAPAL's capacity to adopt this technology.

2. Materials and Methods

2.1 Approach and study design

This work adopts a comparative technical-synthesis design (a technology-transfer design study), not a primary experimental trial. The quantitative evidence reported in Section 3 comes exclusively from DOI-verified indexed sources, fully referenced in Section 6. No field experimental data are generated or presented as the author's own; the experimental design proposed in Section 2.4 is a methodological proposal for a subsequent pilot phase, not executed within this manuscript. This scope delimitation directly responds to prior editorial observations on methodological robustness and is intended to prevent any mismatch between conclusions and the evidence presented.

2.2 Reference technological configuration (Netherlands)

The documented reference configuration combines: (a) a high-rate A-stage with short hydraulic retention time, aimed at capturing the largest possible fraction of particulate COD through chemically enhanced primary treatment (CEPT); (b) a B-stage of partial nitritation (PN) followed by ANAMMOX, in granular-sludge or fixed-film reactors; (c) anaerobic digestion of primary and secondary sludge, with energy recovery through biogas cogeneration; and (d) phosphorus recovery from the digester supernatant through controlled struvite crystallisation [1, 3, 6, 8, 9, 10].

2.3 Chemical and stoichiometric basis

Partial nitritation (partial aerobic oxidation of ammonium to nitrite) is described by:

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + H_2O + 2\ H^+ \quad (1)$$

The stoichiometry of the ANAMMOX process, established experimentally by Strous et al. [1] via mass balance in a sequencing batch reactor, is expressed as:

$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O \quad (2)$$

This stoichiometric ratio (NH4+ : NO2− : NO3− ≈ 1 : 1.32 : 0.26) underlies the design of the nitrite/ammonium ratio required in the PN stage and implies that approximately 57% of the influent ammonium must be oxidised to nitrite in the PN stage, leaving the remainder available as reduced substrate for ANAMMOX [1, 6].

Phosphorus crystallisation as struvite, used to recover nutrients from the digester supernatant, follows the precipitation reaction:

$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6\ H_2O \rightarrow MgNH_4PO_4{\cdot}6H_2O$ (struvite)↓ (3)

The crystalline product contains 51.8% P2O5 (on a MgNH4PO4 basis), making it suitable as a slow-release fertiliser [10]. The reaction is favoured at pH 8.0–8.5 and can be intensified through electrochemical deposition at neutral pH [9].

For verification of the pathogen multi-barrier in potable reuse, the standard log-reduction indicator is used:

$LRV = \log_{10}(C_{in} / C_{out})$ (4)

where Cin and Cout are the reference-organism concentrations before and after the evaluated barrier process. The documented reference values for direct potable reuse (approximately 12-log for enteric viruses, 10-log for Giardia, and 10-log for Cryptosporidium, per treatment credit frameworks) constitute the proposed starting point for designing the Peruvian multi-barrier train [11, 12, 13].

2.4 Proposed experimental design for the Peruvian pilot phase

A granular sequencing batch reactor (SBR) pilot unit of 20–50 L working volume is proposed, operated in fill–react–settle–draw cycles, controlling: temperature (25–30°C, favourable given the warm coastal/Andean climate), dissolved oxygen (0.3–0.8 mg/L during the partial aerobic phase), solids retention time (> 15 days, to favour the slow growth rate documented for ANAMMOX bacteria), and the influent NO2−/NH4 + ratio to the ANAMMOX stage (target 1.3:1, per Eq. 2).

2.4.1 Tools and materials

• Polycarbonate or transparent PVC SBR reactors (20–50 L), with intermittent aeration controlled by a timed solenoid valve and fine-bubble diffusers. • Probes and sensors: in-line optical dissolved-oxygen probe, pH/ORP probe, conductivity probe, low-cost PLC controller for cycle automation. • Inoculation system with granular ANAMMOX biomass (sourced from a reference plant or cultivated by progressive enrichment, since no commercial ANAMMOX inoculum is currently available in Peru). • UV-Vis spectrophotometer or HACH-type colorimetric kit for N-NH4+, N-NO2−, N-NO3−, and PO4 3 − determination. • COD digestion equipment (heating-block digestion reactor) and analytical balance. • Pilot-scale struvite crystallisation reactor (stirred tank with MgCl2 dosing and pH control via NaOH). • Polishing train: hollow-fibre ultrafiltration (UF) module, pilot-scale reverse osmosis (RO) module, and a UV/AOP reactor (hydrogen peroxide + UV) for advanced oxidation.

2.4.2 Construction procedure

1. Influent characterisation (composition, flow rate, seasonal variability) at the selected SEDAPAL pilot WWTP. 2. Installation of the A-stage: rapid-mix tank with coagulant dosing (ferric chloride or aluminium sulphate) for chemically enhanced primary treatment, with a hydraulic retention time of 20–40 minutes. 3. Construction and inoculation of the PN/ANAMMOX SBR reactor: seeding with start-up biomass, initial short cycles (6–8 h) with gradual nitrogen load increase (3–6 month start-up, consistent with the documented slow growth rate of ANAMMOX bacteria) [1]. 4. Installation of the anaerobic sludge digester, with biogas capture and a pilot-scale cogeneration (CHP) engine or flare for initial testing. 5. Installation of the struvite crystallisation reactor, fed by the digester

supernatant. 6. Installation of the polishing train (UF → RO → UV/AOP) for the fraction destined for potable-reuse testing. 7. Staged start-up with daily monitoring during the first 90 days.

2.5 Chemical assays and analytical quality control

The following assays are proposed, with minimum recommended frequency, following principles harmonised with standard water-analysis methods (APHA/AWWA/WEF) adapted to reagent availability in Peruvian laboratories: • Ammoniacal nitrogen (NH_4^+): Nessler colorimetric method or ion-selective electrode, daily on each stage's effluent. • Nitrite (NO_2^-) and nitrate (NO_3^-): colorimetric method (sulfanilamide/NED) or ion chromatography, daily. • Chemical oxygen demand (COD): closed-reflux dichromate method, three times per week. • Total and volatile suspended solids (TSS/VSS): gravimetry, weekly. • Soluble reactive phosphorus (PO_4^{3-}): ascorbic acid method, three times per week. • pH, temperature, dissolved oxygen, redox potential: continuous, in-line. • Specific ANAMMOX activity (SAA): batch respirometric or substrate-consumption assay, monthly. • Microbiological analysis: total and thermotolerant coliforms, Escherichia coli, helminth eggs, and, where possible, viral indicators (somatic coliphages) before and after each polishing barrier, to compute LRV per Eq. 4.

2.6 Potabilisation verification protocol

Potabilisation verification is proposed in five sequential stages, aligned with Peru's Drinking Water Quality Regulation (Supreme Decree No. 031-2010-SA) and the WHO Guidelines for Drinking-water Quality:

Stage 1 — Baseline characterisation: sampling of the tertiary effluent (post-UF) for the 26 physicochemical and microbiological parameters established in Supreme Decree No. 031-2010-SA (turbidity, colour, pH, residual chlorine, metals, organic compounds, microbiological indicators). Stage 2 — Pathogen barrier validation: determination of the unit-specific LRV (UF, RO, UV/AOP) through controlled seeding of indicator organisms or MS2/PRD1 bacteriophage surrogates, comparing inlet and outlet concentrations per Eq. 4. Stage 3 — Chemical stability testing: verification of the absence of disinfection by-products (trihalomethanes, bromate) and of biofilm reformation in a simulated distribution network (24 h and 48 h chlorine-demand testing). Stage 4 — Acute toxicity testing: bioassay with Daphnia magna or Vibrio fischeri on the final effluent, as an additional non-specific safety barrier. Stage 5 — Documentary verification and traceability: compilation of continuous operating records (minimum 12 months) and statistical comparison against maximum permissible limits, as the basis for sanitary certification before Peru's General Directorate of Environmental Health (DIGESA) and the National Superintendency of Sanitation Services (SUNASS).

2.7 Ethical considerations

This study consists of a technical synthesis of published literature and an engineering design proposal; it does not involve experimentation with humans or animals, nor the collection of personal data, and therefore does not require research ethics committee approval. Should the pilot phase described in Section 2.4 be executed, it must first receive approval from the institutional ethics committee of Universidad Autónoma del Perú and the corresponding environmental and sanitary permits from the competent Peruvian authorities (ANA, DIGESA, SUNASS), which is stated as a condition for its future execution.

3. Results

3.1 Quantitative comparison matrix

Table 1

synthesises the quantitative indicators documented in the verified literature (Section 6), comparing the conventional nitrification–denitrification/chlorination configuration with the PN/ANAMMOX plus phosphorus-recovery configuration implemented in the Netherlands, and its adaptation potential for SEDAPAL's operations in Peru.

Indicator / parameter	Conventional configuration (N-DN + Cl2)	PN/ANAMMOX + P-recovery configuration (Netherlands)	Adaptation potential for Peru (SEDAPAL)	Source (DOI)
Aeration demand (energy) for N removal	Baseline (100%)	Reported reduction of up to ~ 60% versus conventional nitrification-denitrification, since full oxidation to nitrate and external carbon are not required	Applicable to SEDAPAL peri-urban WWTPs with medium-high domestic N loads; requires DO control < 0.5 mg/L	10.1126/science.1185941
External organic carbon requirement	Yes (methanol/ethanol) in denitrification	Not required; ANAMMOX is autotrophic (uses CO2/HCO3- as carbon source)	Reduces reagent operating costs in resource-constrained Peruvian plants	10.1007/s002530051340
Plant footprint reduction (Nereda granular technology)	Baseline	Up to 70% less surface area than conventional activated sludge	Relevant for WWTP expansions in dense urban areas of Lima	10.1007/s00267-018-0995-8
Nereda process energy savings	Baseline	Up to 50% reduction in energy consumption	Compatible with energy-neutrality targets of Peruvian water utilities (EPS)	10.1007/s00267-018-0995-8
Biogas production / energy self-sufficiency (NL water authorities)	Variable, dependent on conventional digestion	116 million m3/year of biogas; revenue ≈ €24 million/year; covers ~ 40% of water authorities' energy consumption (2030 projection: 200 million m3/year)	Scalable to large SEDAPAL WWTPs with sludge co-digestion	10.1007/s00267-018-0995-8
Phosphorus recovery as struvite	Not contemplated (P discharged or precipitated as non-valorised sludge)	Struvite (MgNH4PO4·6H2O), 51.8% P2O5 content, suitable as slow-release fertilizer	Additional revenue opportunity for SEDAPAL through sales to the agricultural sector	10.1021/es401140s
Log10 pathogen reduction required for direct	Determined case-by-case; no unified framework	Proposed reference values: ~12-log enteric viruses, ~ 10-log Giardia, ~ 10-log	Technical basis for SEDAPAL to design a Peruvian potable-reuse	10.1016/j.watres.2017.10.034

Indicator / parameter	Conventional configuration (N-DN + Cl2)	PN/ANAMMOX + P-recovery configuration (Netherlands)	Adaptation potential for Peru (SEDAPAL)	Source (DOI)
potable reuse		Cryptosporidium (treatment credit framework)	regulatory framework, aligned with Supreme Decree No. 031-2010-SA	
Multi-barrier reliability framework	Ad hoc	Pathogen credit framework with barrier redundancy	Applicable to the design of multi-barrier treatment trains in SEDAPAL plants	10.1016/j.watres.2015.07.024
Institutional adoption determinants of reuse (Peruvian context)	Not systematically modelled	N/A (study conducted in Peru)	External regulatory pressure (β = 0.345) and institutional framework quality (β = 0.287) are the strongest predictors of implementation (R2 = 82.3% on results); organisational resources β = 0.273	10.3390/w18050596
MBR sustainability framework for reuse (South America)	Not systematically applied in the region	Transferable ICoS methodological reference	Applicable to evaluate sustainability of reuse technologies in Peruvian EPS utilities	10.1016/j.mex.2023.102111

Table 1. *Quantitative comparison matrix of documented indicators (Netherlands) versus conventional configuration and adaptation potential for Peru. Author's own elaboration based on the references cited in each row.*

3.2 Process figure

3.3 Energy balance synthesis

The documented evidence indicates that replacing conventional nitrification–denitrification with PN/ANAMMOX reduces aeration demand — the largest electricity-consuming component of a WWTP — because only a fraction of the ammonium requires full aerobic oxidation (Eq. 1), while the rest is converted anaerobically via ANAMMOX (Eq. 2) without external organic carbon [1, 2, 6]. This reduction in aerobic consumption, combined with energy recovery from anaerobic sludge digestion (documented at 116 million m3/year of biogas, covering ~ 40% of the sector's energy consumption in the Netherlands) [8], supports the conceptual feasibility of energy neutrality as a design objective for medium-to-large Peruvian plants.

3.4 Expected results of the proposed potabilisation protocol

Based on the log-reduction reference values reported in the potable-reuse literature [11, 12, 13], the proposed multi-barrier train (UF + RO + UV/AOP), described in Section 2.4.1, combined with the microbiological reduction already achieved by PN/ANAMMOX biological treatment, is expected to cumulatively reach the internationally required orders of magnitude of log reduction for enteric viruses, Giardia, and Cryptosporidium. This is a technical projection based on the documented performance of each barrier unit in the cited literature, and must be confirmed through controlled-seeding tests during the pilot phase (Stage 2, Section 2.6), not through data generated in this manuscript.

4. Discussion

4.1 Technical transferability from the Netherlands to Peru

Peru's coastal and Andean climatic conditions, with wastewater temperatures typically between 20 and 28°C, are in principle more favourable for ANAMMOX kinetics than the Netherlands' temperate climate, where mainstream-configuration operational limitations have been documented at 10–15°C [3, 4]. This thermal advantage constitutes a favourable technical argument for the Peruvian adaptation, although it must be experimentally validated, since the literature reviewed does not include mainstream ANAMMOX studies specific to Peru's tropical/Andean climate.

4.2 SEDAPAL's institutional capacity: empirical evidence

Adoption-capacity assessment cannot rest on technical feasibility alone. The structural equation modelling study of 150 organisational decision-makers in Lima, Trujillo, and Cajamarca [15] provides direct, recent empirical evidence on the determinants of water reuse technology adoption in Peru. According to that study, external regulatory pressure ($\beta = 0.345$; $p < 0.001$) and institutional framework quality ($\beta = 0.287$; $p < 0.001$) are the strongest predictors of effective implementation, outweighing organisational resource availability ($\beta = 0.273$) and pro-environmental organisational culture ($\beta = 0.255$). Notably, favourable individual attitudes did not translate into greater implementation but showed a negative association ($\beta = -0.350$), interpreted as a possible gap between favourable perception and actual structural capacity [15].

This evidence suggests that, for SEDAPAL to adopt the ANAMMOX/nutrient-recovery technology described in this article, the critical variable is not solely budget or trained-personnel availability, but rather the existence of an explicit regulatory framework for potable reuse (currently absent or incomplete in Peruvian regulation) and regulatory-pressure mechanisms (mandatory targets, discharge standards, tariff incentives) that create the necessary institutional incentive. In its current state, SEDAPAL possesses the engineering capacity to operate advanced biological processes but faces — according to evidence documented for the broader Peruvian context — regulatory fragmentation across multiple agencies with overlapping competencies [15], which constitutes the principal non-technical barrier identified.

4.3 Study limitations

This manuscript has explicit methodological limitations, stated to prevent any mismatch between conclusions and the evidence presented: (a) no primary experimental data were generated; the quantitative values in Table 1 come from documented sources, not from the author's own measurements; (b) the experimental design in Section 2.4 is a methodological proposal pending pilot execution; (c) no mainstream ANAMMOX studies specific to Peruvian climate conditions are available, so the performance projections in Section 3.4 should be interpreted as technical hypotheses to be validated, not as confirmed results; (d) the assessment of SEDAPAL's institutional capacity relies on published empirical evidence on the broader Peruvian context of reuse-technology adoption [15], not on a primary study directed specifically at SEDAPAL as a single case.

5. Conclusions

Documented evidence from the Netherlands shows that integrating PN/ANAMMOX, phosphorus recovery as struvite, and anaerobic digestion enables progress toward energy neutrality and nutrient recovery in water treatment plants, with aeration reductions of up to ~ 60%, energy savings of up to 50%, and footprint reductions of up to 70% in associated technologies, alongside documented revenue generation from biogas and phosphorus recovery [1, 2, 6, 8, 9, 10]. These figures, although not obtained by the author, constitute a solid and verifiable technical basis for justifying a technology-transfer protocol to Peru.

The technical protocol proposed in this article — including tools, construction procedures, chemical assays, and a five-stage potabilisation verification protocol — offers a concrete, non-generic operational path for SEDAPAL to evaluate adoption of this technology. However, empirical evidence on adoption determinants in the Peruvian context [15] indicates that technical feasibility is a necessary but insufficient condition: the most likely limiting factor is not process engineering, but the absence of an explicit potable-reuse regulatory framework and the institutional fragmentation of Peru's sanitation sector. Any SEDAPAL pilot initiative in this direction should be accompanied, from its design stage, by a regulatory-strengthening component, and future work should provide the primary experimental data that this technical-comparative manuscript does not generate.

Declarations

Ethics approval: Not applicable; the study did not involve humans, animals, or personal data. See Section 2.7 for the ethical requirements of a future pilot phase.

Competing interests: The author declares no competing interests.

Funding: This study received no external funding.

Data availability: No primary experimental datasets were generated; all quantitative information derives from the sources cited in Section 6.

Author contribution: Paul Ricardo Prudencio Galvez conceived the study, conducted the literature review, designed the proposed technical protocol, and wrote the manuscript in its entirety.

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Figures

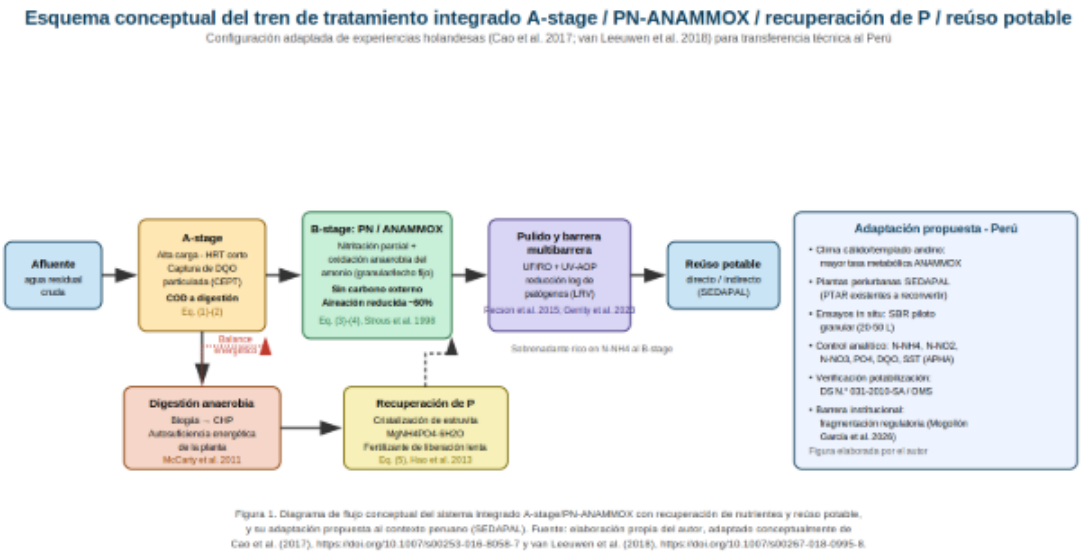


Figura 1. Diagrama de flujo conceptual del sistema integrado A-stage/PN-ANAMMOX con recuperación de nutrientes y reúso potable, y su adaptación propuesta al contexto peruano (SEDAPAL). Fuente: elaboración propia del autor, adaptado conceptualmente de Cao et al. (2017), https://doi.org/10.1007/s00253-016-8058-7 y van Leeuwen et al. (2018), https://doi.org/10.1007/s00267-018-0995-8.

Figure 1

Conceptual flow diagram of the integrated A-stage/PN-ANAMMOX system with nutrient recovery and potable reuse, and its proposed adaptation to the Peruvian context (SEDAPAL). Author's own elaboration, conceptually adapted from Cao et al. [6] and van Leeuwen et al. [8].