

Sustainable nitrate remediation techniques within a circular economy framework

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Nitrate is a common pollutant originating from the extensive use of fertilizers in agricultural areas. Its presence in water resources poses a public health concern, as ingestion of nitrate-contaminated water has been associated with methemoglobinemia and an increased risk of colorectal cancer. In addition, it also threatens aquatic ecosystems by promoting eutrophication processes. Regulatory measures aimed at limiting fertilizer application have been implemented since the 1990s. However, nitrate pollution remains widespread, and many water bodies still exceed established regulatory thresholds, which in Spain are set at 37.5 mg/l for groundwater and 25 mg/l for surface waters (RD 47/2022), making nitrate a persistent socio-environmental and socio-economic challenge.

This contribution investigates nature-based strategies to mitigate nitrate pollution by enhancing microbial denitrification, a natural process that transforms nitrate into inert nitrogen gas when an electron donor, such as organic carbon, is available. Denitrification in waterbodies is often limited by organic carbon scarcity. As a result, a potential remediation strategy is the injection of pure organic carbon-rich compounds into nitrate-polluted water bodies. However, the use of pure compounds is costly and might involve production-related constraints that may limit their sustainability at large scales, highlighting the need for cost-effective alternatives such as agro-industrial by-products, in line with circular-economy principles. In this context, we evaluated the use of whey, a dairy by-product, as an external electron donor to stimulate denitrification in different polluted water bodies. The study followed an integrated approach combining laboratory experiments, pilot-scale field applications, and stable isotope analyses ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}\text{-NO}_3$).

The laboratory experiments proved the feasibility of whey as an electron donor for denitrification. Also, nitrogen and oxygen isotope fractionation values in nitrate ($\epsilon^{15}\text{N}$ and $\epsilon^{18}\text{O}$) were determined and used as a process-based validation tool beyond concentration-based assessments, as denitrification produces a distinctive isotopic fingerprint.

Pilot-scale field applications were then conducted in two complementary systems affected by agricultural nitrate pollution: a constructed wetland treating agricultural runoff in Ejea de los Caballeros (Zaragoza), and the Quaternary Campo de Cartagena aquifer that discharges into the Mar Menor coastal lagoon. In both sites, nitrate concentrations exceeding 200 mg/L have been measured. The results demonstrated that whey-based biostimulation can substantially reduce nitrate concentrations under regulatory thresholds when dosing and hydraulic conditions are

appropriately managed in both systems. Isotopic analyses proved essential for quantifying the efficiency of the remediation strategy at field-scale.

Beyond technical performance, this strategy contributes to the creation of sustainable socio-environmental scenarios by promoting circular reuse of agro-industrial residues and reducing remediation costs in nitrate mitigation measures. The integration of nature-based solutions with isotopic evidence provides a transferable framework to support sustainable water remediation in agricultural landscapes facing chronic nitrate pollution.

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