

pollution linked to prolonged cage farming and low current speed (Cai et al., 2023). Comparative surveys around grouper cages further demonstrate significantly elevated dissolved inorganic nitrogen and soluble reactive phosphorus relative to non-aquaculture waters, identifying these nutrient indicators as central to assessing eutrophication pressure in cage-culture zones (Liu et al., 2024).

Inputs and Fate of Nitrogen (N), Phosphorus (P) and Organic Carbon (OC) in Marine Cage Aquaculture of Groupers

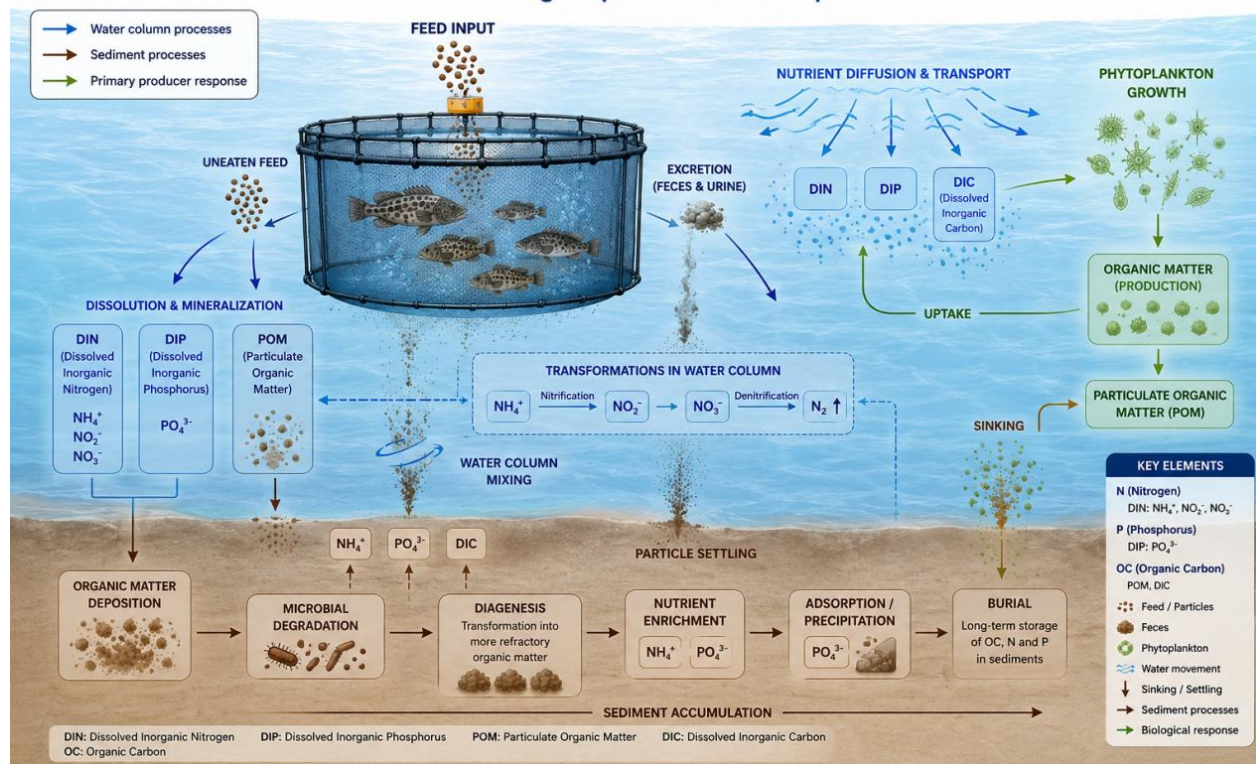


Figure 1 Conceptual pathways of nitrogen, phosphorus, and organic carbon release from grouper cage aquaculture and their transport into the surrounding water column and sediments

Note: Uneaten feed and fish feces are the primary sources of nutrient inputs in cage aquaculture. Released dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and particulate organic matter (POM) contribute to eutrophication and organic enrichment of sediments

3.3 Biological indicators and microbial community characteristics

Biological indicators, especially microbial communities, provide sensitive and integrative measures of water quality changes in cage aquaculture environments. Comparative metagenomic analysis between grouper cages and nearby non-farmed waters has shown that bacterial diversity and functional genes related to carbon, nitrogen, and sulfur metabolism are significantly altered where eutrophication indicators are elevated (Liu et al., 2024). Correlation analyses indicate that many microbial taxa increase with dissolved inorganic nitrogen and soluble reactive phosphorus but decrease with DO, linking microbial assemblages directly to physicochemical and nutrient indicators.

Beyond planktonic bacteria, broader microbiome-based approaches emphasize microorganisms as both indicators and managers of water quality. Conceptual frameworks propose using shifts in microbial nitrogen and phosphorus transport and metabolism, together with community composition, as early-warning signals of self-pollution and environmental impact in aquaculture systems. Field studies in marine reservoirs with net-cage culture report elevated total heterotrophic bacteria and more frequent detection of fecal indicators such as *Escherichia coli* at cage sites compared with reference locations, illustrating how microbial counts and specific taxa can serve as practical biological indicators of organic loading and contamination in cage-culture waters.