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# Exploring the Potential of Algal-Bacterial Consortia for Nutrient Recovery from Aquaculture Effluents

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**Abstract:** Aquaculture effluents contain nutrients that could induce eutrophication but could also help produce recoverable microbial biomass. There are a number of potential options to integrate effluent treatment with nutrient harvest through algal-bacterial consortia. It should be noted that dissolved nutrient removal does not automatically imply resource recovery. In this paper, the stoichiometric approach is developed to calculate the portion of nutrient input exported in consortium biomass. Experimental data obtained recently provide a process description, while all numerical results were calculated on the basis of explicitly described hypothetical cases. The proposed model takes into account both nutrient limitations of biomass production, a first-order approach to the biomass capacity, and an independent biomass recovery factor. Four nitrogen-to-phosphorus mass ratios in the inflow at an available nitrogen concentration of 20 mg N $L^{-1}$ were studied. At six days and 85% biomass capture, 70.95%, 70.95%, 42.57%, and 26.61% nitrogen recovery is calculated for 4:1, 6:1, 10:1, and 16:1 N:P ratios, respectively. Phosphorus recovery is 47.30%, 70.95%, 70.95%, and 70.95%. With the ratio of 6:1, phosphorus recovery rises from 50.08% to 79.30% when biomass capture is increased from 60% to 95%. These results show that nutrient balance and harvest limit the recoverable mass. They do not prove treatment performance, consortium superiority, or product suitability. Confirmation necessitates full nutrient balances, independent biomass analysis, and effluent experiment replication. The approach offers a clear starting point for nutrient recovery research design and the difference between nutrient conversion, biomass accumulation, and export.

**Keywords:** Algal-Bacterial Consortia; Aquaculture Effluent; Nitrogen Recovery; Phosphorus Recovery; Biomass Harvesting; Nutrient Balance.

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## I. Introduction

The biological removal of pollutants from aquaculture effluent may be achieved in combination with the creation of microbial biomass. This has been proven experimentally using algae and indigenous bacteria in wastewater from shrimp farming (Bhatt et al., 2024). The issue that needs to be addressed is not just the reduction in the level of nutrients but rather the removal of a part of the initial biomass of nutrients.

### *1.1 From Effluent Treatment to Recoverable Nutrient Mass*

The chemical forms of dissolved nutrients as well as their biological accessibility differ between aquaculture effluents. A comparative study of bacteria, cyanobacteria, and green microalgae cultivated in fish effluent illustrates that the distinction between nitrogen species and substrate accessibility should be considered in the treatment performance evaluation (Aranda-Vega et al., 2024). In terms of biomass recovery potential, a measure of the total input nutrient inventory may not fully reflect the portion accessible during the limited cultivation time interval. Pretreatment, mineralization, and analytical fractionation have implications for the interpretation of the initial inventory.

Separation of biomass is yet another limiting factor. An experimental investigation of intensive marine aquaculture demonstrates that consortium cultivation and harvesting with subsequent effluent polishing are part of a single recovery sequence (Perales-Pérez et al., 2023). The nutrients stored in the suspended cells are present in the treated effluent waters until those cells are isolated. It is therefore possible to see a drop in the dissolved nutrient concentration concurrent with an incomplete removal of the nutrient mass from the treated stream. The point is quantitatively significant. The recovery of only a portion of the input inorganic nitrogen as organic nitrogen in biomass is seen from the investigation of granular sludge used in

aquaculture (Zhang et al., 2023). This is an indication of why it is not possible to automatically equate removal percent to recovery percent. Nitrogen transformed into a gas, for instance, will not contribute anything to biomass but will clean up the water body.

### *1.2 Aim and Scope*

The goal is to investigate how nutrient availability balance and biomass harvest limit nitrogen and phosphorus recovery by algal-bacterial consortia. The goals are to establish the limits of recovery, construct a biomass equation for nutrient-limited situations, compare different influent N:P ratios, and examine the impact of harvest. Two results are harvested nitrogen recovery and harvested phosphorus recovery, expressed as a fraction of the respective influent nutrient load. This paper is analytical, and does not introduce any new effluents or cultures. The value of this paper is its framework for audit and its testable implications. The calculations do not duplicate a reactor model, identify a general optimal condition, or illustrate microbial interactions.

## II. Literature Review

An algae-bacteria system is capable of having more than one pathway for the retention of nutrients within a given time period. While biomass assimilation maintains the nutrients within the cells, microbial nitrogen transformation has the ability to alter its chemical form and cause its gaseous loss. The influence of environmental factors may vary depending on the contribution of both pathways. Studies conducted on brackish and marine aquaculture granular systems revealed that salinity changes the ratio of nitrogen transformation and nitrogen assimilation (Zhang et al., 2025). The use of indigenous communities can be considered feasible due to the fact that biomass retention will be comparatively easier in such cases. Evidence that extends endogenous algal communities from cultivation to pilot systems of aquaculture proves the usefulness of such research (Yang & Lu, 2025).

There is another path to be followed in terms of designed community configurations. The combination of algae with immobilized bacteria in relation to aquaculture treatment along with pathogenic microorganisms and antibiotic resistance genes is discussed in a scientific study (Sun et al., 2025). The comprehensive view of this research indicates that nutrient performance is not the only parameter to consider for system evaluation. In the case of nutrient-rich harvests, they act as intermediate products that need to be analyzed separately in terms of their nature and intended use. Community analysis can serve as an aid for understanding the difference in treatment. The recent investigation regarding algal-bacterial communities in the aquaculture effluent system demonstrates a relationship between community structure and nutrient change via multivariate analysis (Wang et al., 2026).

Co-cultivation experiments can also be used to make direct comparisons between algal species. Studies using Chlorella sp. and Phaeodactylum tricornutum have been conducted in order to understand pollutant removal and resource recovery in marine aquaculture wastewaters (Ding et al., 2024). This information is pertinent to culture selection, but a comparative study of algae does not necessarily identify the role of bacteria independently. It is important to distinguish between the composition of the consortium and the process that is responsible for the performance difference. The attached growth systems solve the separation issue. A rotating algal biofilm reactor has been studied for simultaneous removal of pollutants and nutrients from mariculture wastewater (Zhang et al., 2024). Keeping the biomass on the surface changes the light availability and harvesting logistics. However, the weight of detached, harvested, and exported biomass needs to be determined.

Studies on continuous flow microalgae and indigenous bacteria indicate the relevance of retention time and microbial interactions to the advanced treatment of secondary effluent (Li et al., 2024). This is related evidence, not an aquaculture-specific calibration study. Biological harvesting presents a third possibility, where Daphnia magna is used to eat algae cultivated on recirculating aquaculture effluent, and nutrients are transferred to a second biological compartment (Gorzelnik et al., 2023). This method would need the consideration of further trophic losses. There is a range of biological systems described in literature;

however, percentages of treatment and nutrient fractions are different concepts. The current analysis takes into account this conceptual difference by considering nitrogen and phosphorus balances simultaneously. Performance values from the literature are not combined due to differences in wastewater composition, reactor operation, nutrient fractions, and harvest definition. All model parameters are assumptions.

# III. Materials and Methods

## *3.1 Analytical Design and Scenario Boundary*

The deterministic batch simulation model consists of algal-bacterial culturing period and biomass harvesting only once. The process is preceded by the solids separation or solubilization processes, if any. Consequently, initial nutrient amounts are available nitrogen and phosphorus amounts present in the cultivation liquid and are not equal to total amounts of nutrients supplied to the fish farm. There are no further nutrients supplied to the modeled batch process. The water quantity does not change and balances are done on one-liter cultivation liquid. Four influent nitrogen-to-phosphorus ratios (r) of 4, 6, 10, and 16 are analyzed. The nitrogen availability is constant and amounts $N_0$ = 20 mgN/l, while phosphorous availability amount is equal to $N_0/r$, so 5.00, 3.33, 2.00, 1.25 mgP/l. It should be emphasized that there is no measurement of such values, rather it is some artificial data provided.

## *3.2 Biomass Composition and Nutrient Capacity*

The assumed nitrogen and phosphorus fraction of newly created dry biomass consortium are fN=0.06 g element $g^{-1}$ dry biomass and fP=0.01 g element $g^{-1}$ dry biomass respectively, making the mass ratio N:P to be 6:1. The assumed fraction consists of both algal and bacterial components but does not imply any particular combination of the species present. No physiological storage, cell quota variability, or algal-to-bacteria ratio adjustment are considered in this initial assumption.

$$Blim = min(Bmax, N_0/fN, P_0/fP) \quad (1)$$

The blim is the nutrient-limited potential for net dry biomass production in mg $L^{-1}$. Bmax = 400 mg $L^{-1}$ is the theoretical non-nutrient potential for dry biomass production reflecting the limitations imposed by space, light, carbon availability, and other factors. An elemental concentration divided by its dimensionless biomass mass fraction produces the dry biomass concentration. Equation (1) ensures that the amount of each element consumed by the predicted growth does not exceed the initial amount. The capacity is 333.33 mg $L^{-1}$ at the ratio 4:1 and 6:1, 200.00 mg $L^{-1}$ at 10:1, and 125.00 mg $L^{-1}$ at 16:1. Nitrogen is the limiting element at 4:1, both elements are equally available at 6:1, and phosphorus is the limiting element at the higher ratios in the specified composition. Bmax is not the limiting factor in these four cases.

## *3.3 Time Dependence*

$$B(t) = Blim \times [1 - exp(-kt)] \quad (2)$$

Here, B(t) represents net dry biomass formed up to batch time t in days, and k = 0.30 d-1 represents an arbitrary rate constant. The simulation runs from 0-10 days, with a critical comparison point at six days. Equation (2) reaches the carrying capacity monotonically and starts off from zero net biomass; it is simply a phenomenological account of biomass production and not growth rate.

## *3.4 Harvested Nitrogen and Phosphorus Metrics*

Nutrient uptake is separate from harvesting in the model. η is the proportion of consortium biomass generated that is recovered during the final solid/liquid separation process. Default is η = 0.85, but other values, 0.60 and 0.95, are used to evaluate sensitivity to harvesting efficiency. Harvesting is nonspecific, which means that the elemental composition of the biomass not recovered is identical to that which was recovered. Inoculum biomass is excluded from harvest recovery because it does not count against nutrients added in equation (3).

$$HN = \eta f N\, B(t); \quad HP = \eta f P\, B(t) \tag{3}$$

Mass HN and HP refer to mass exports of nitrogen and phosphorus contained in the newly generated biomass, measured in mg element per liter of the original growing solution ($L^{-1}$). The selection of this measurement makes it possible to distinguish between an increase in the water concentration and the obtained product itself. Any further processing of the biomass does not affect its marketability.

$$RN = 100HN/N_0; \quad RP = 100HP/P_0 \tag{4}$$

RN = nitrogen recovery, the measure presented in figure 1. RP = phosphorus recovery, the measure presented in figure 2. The denominators represent the initial inventories of the elements in equation (4). Equal percentage recovery does not mean equal mass because the inventories of nitrogen and phosphorus are not the same. If one were to consider total farm input recovery, a broader denominator would be needed.

### *3.5 Mass Balance and Omitted Pathways*

$$E_0 = [E_0 - fE\, B(t)] + (1 - \eta) fE\, B(t) + \eta fE\, B(t) \tag{5}$$

For E being nitrogen or phosphorus, equation (5) divides the initial stock into residual dissolved nutrient, nutrient contained in unharvested new biomass, and nutrient in harvested new biomass. The three stock compartments add up to the total input. The inoculum composition is kept out of this net balance. With the simplifying assumptions made, the dissolved depletion is assimilation, and the recovery also includes the harvesting process. Nitrification without depletion alters the form of the nitrogen but does not affect the total elemental stock.

The model does not take into account denitrification, ammonia volatilization, precipitation, wall sorption, luxury phosphorus uptake, decay, grazing, and nutrient exchange with the retained initial cells. These processes can occur in real reactors, and hence the reduction of the concentration cannot be attributed to biomass assimilation without further information. In a future expansion, all these pathways need to be included as separate mass stocks.

### *3.6 Calculation Checks and Interpretation*

The values are all calculated prior to rounding. The checks include only nonnegative residual inventories, where $0 \leq RN \leq 100$, $0 \leq RP \leq 100$, no recovery for $t = 0$ or $\eta = 0$, and exact balancing of equation (5). Statistical analysis is unnecessary, as the scenarios are deterministic in nature. The harvest possibilities are conditional, not a measure of uncertainty. The following equations and variables should be sufficient to recreate figures 1 and 2, using no raw experimental data.

## IV. Results

### *4.1 Nitrogen Recovery During Batch Cultivation*

Figure 1 below represents nitrogen recovery pathways. With respect to six days and baseline biomass capturing, RN is 70.95% with N:P ratio of 6:1, 42.57% with N:P ratio of 10:1, and 26.61% with N:P ratio of 16:1. Not shown in the graph since they coincide exactly are the nitrogen pathway with 4:1 and 6:1 ratios since they both share the same constrained biomass nitrogen capacity.

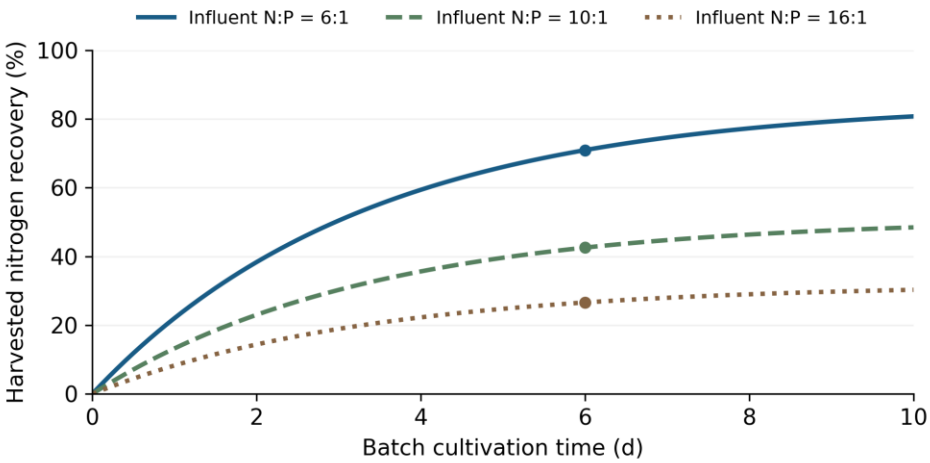



Figure 1: Calculated Harvested Nitrogen Recovery During Synthetic Batch Cultivation

However, the difference between the balanced condition and phosphorus limitation continues to exist even when time increases. For instance, in ten days, RN for ratio 6:1, 10:1, and 16:1 will be 80.77%, 48.46%, and 30.29%, respectively. The limiting values of all of them in the long run will be 85.00%, 51.00%, and 31.88%, respectively, which is defined by nutrient carrying capacity and 85% of capture efficiency.

### *4.2 Nitrogen Mass Behind the Percentages*

At day 6, nitrogen recovery is 14.19 mg N $L^{-1}$ for the 6:1 condition, which is more than 8.51 and 5.32 mg N $L^{-1}$ for 10:1 and 16:1 condition. This difference between 6:1 and 16:1 equals 8.87 mg N $L^{-1}$, or 44.34 percentage points of the common starting nitrogen stock. These discrepancies are based on the phosphate availability in the chosen model and are not quantitative differences between consortia or superior growth of any culture.

### *4.3 Phosphorus Recovery Under Alternative Harvesting Conditions*

Phosphorus recovery in figure 2 is shown at day six. RP for the control is 47.30% at 4:1 and 70.95% at all other ratios. In case of 4:1, nitrogen becomes the limiting factor for biomass production, but phosphorus is available in plenty. Above ratio of 6:1, phosphorus becomes the limiting factor for biomass production, so its recovery percentage stays the same despite decreasing mass.

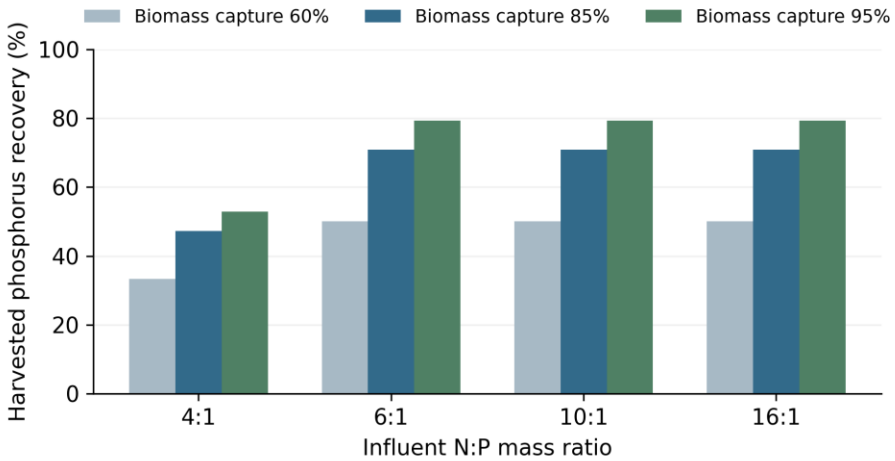



Figure 2: Calculated Harvested Phosphorus Recovery at Day Six Across Synthetic Influent

At the balanced ratio, as the percentage of capture increases from 60% to 95%, the percentage increase of RP from 50.08% to 79.30%, which equals a total percentage change of 29.21%. This is due to the fact that the above percentages are also obtained at 10:1 and 16:1 ratio since phosphorus is the limiting element. At 4:1 ratio, the above percentages equal 33.39% and 52.86% respectively.

### *4.4 Paired Nutrient Outcomes and the Recovery Boundary*

The absolute phosphorus harvest at day 6 and $\eta = 0.85$ is 2.36 mg P $L^{-1}$ for 4:1 and 6:1, then 1.42 and 0.89 mg P $L^{-1}$ for 10:1 and 16:1, respectively. Hence, equal phosphorus percentages for the three higher ratios indicate different masses of products. In 6:1 ratio, 83.47% of each nutrient is absorbed before harvest, while only 70.95% is harvested in biomass form. The rest 12.52% is linked with uncaptured new biomass. Hence, the dissolved depletion overestimates the recovered mass when the separation process is not considered in the accounting boundary.

## V. Discussion

### *5.1 What the Nutrient Balance Demonstrates*

Calculations reveal that cultivation and harvest favorably are mutually complementary processes. At the given consortium composition, ratio 6:1 of influent mass ensures the supply of nutrients in correlation with their accumulation in biomass. Above this ratio nitrogen extraction is limited by phosphorus availability, below that there is excess of phosphorus due to limitation of biomass growth by the shortage of nitrogen. Such ratio depends on chosen biomass composition and can't be regarded as optimal for any case of effluent aquaculture use.

Community mixture can change the composition, accumulate phosphorus, release organics' nutrients or loose nitrogen so that to upset such balance. This means that the theoretical curves show hypotheses, but not practical guidelines. Deviation from the model can be considered informative in case when a missed element is present in some other reservoir. In case when mass balance is lost one has to check analytical recoveries, losses in sampling, gaseous compounds formation and solids retention before biological interaction.

### *5.2 Harvesting and Product Interpretation*

The harvest comparison makes the accounting boundary clear. An increase in $\eta$ results in increased recovered mass but leaves the cultivation trajectory unchanged. Published research on cultivation and harvest indicates that biological growth and biomass separation should be evaluated together (Perales-Pérez et al., 2023; Zhang et al., 2024). The separation approach should be evaluated based on the nutrient mass of the harvested material and the suspended mass in the effluent. Total dry solids do not necessarily have to be equal to new biological biomass and may contain mineral precipitates or other treatment chemicals.

Nutrient recovery requires an end use as well. A biomass harvest does not necessarily mean a useful feed material or fertilizer. Species, elemental composition, digestibility or plant availability, residual salts, treatment chemicals, and contaminants affect the appropriateness of reuse. This analysis ends with the harvest and makes no claims regarding the safety, nutritional quality, or fertilizer savings. Nutrient recovery and beneficial reuse should remain distinct steps in the evaluation process.

### *5.3 Validation Priorities and Operating Limits*

Validation must start by collecting several independent samples of effluent and measuring both dissolved and particulate nitrogen and phosphorus. Productivity trials will measure initial inoculum nutrients, final culture solids, biomass harvested, residual particles, and dissolved residues. Controls to account for non-biological losses and carefully designed tests with one partner organism or minimal community are required before claiming any difference is due to the alga-bacteria partnership. Nutrient

masses must be standardized according to volume and time of treatment with appropriate analytical blanks and recoveries.

Outdoor validations must track oxygen, pH, light, salinity, temperature, and flow. Independent validation of salinity and residence time experiments from the literature highlight the necessity of conducting these validations (Zhang et al., 2025; Li et al., 2024). Continuous reactors need to balance hydraulic and solid retention rather than plugging batch time into equation (2). Energy, land use, and downstream processing do not enter into the scope of this paper at present. Biomass proportions and rate constants must be known first.

# VI. Conclusion

Algal-bacterial consortia present a realistic biological option for concentrating aquaculture nutrients as harvestable biomass; however, nutrient recovery should be considered in terms of exported mass. In this analysis, nutrient capacity, batch cultivation time, and biomass capture are linked in a clear nitrogen and phosphorus balance. For a cultivation period of six days and biomass capture of 85%, calculated nitrogen recovery decreases from 70.95% for N:P = 6:1 to 26.61% for 16:1, while phosphorus recovery stays constant at 70.95% as its initial quantity is smaller. For N:P = 4:1, phosphorus recovery is 47.30% because there is excess phosphorus under nitrogen limitation. Increased biomass capture from 60% to 95% increases phosphorus recovery in the balanced scenario from 50.08% to 79.30%. These results are synthetic consequences of assumed conditions, not an outcome of actual consortium activity. This shows that concentration removal does not allow establishing nutrient recovery on its own, and percentage recovery should be accompanied by absolute nutrient mass. Future research should close nutrient balances, assess variable biomass composition, and validate its reuse potential.

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