

Innovative use of Barley Straw to control algal blooms and improve wastewater quality: Microbial community insights in a sustainable pre-filtration conditioning

Atef Mohamed Gad Mohamed^a, Ashraf Ahmed^{b,*}, Eman A. Mahmoud^c, Eman M. Farahat^d, Khaled N.M. Elsayed^{e,g}, Abeer El Shahawy^{f,*}

^a Assiut & New Valley Company for Water and Wastewater, Assiut, Egypt

^b Department of Civil and Environmental Engineering, Brunel University of London, Kingston Lane Uxbridge, UB83PH, UK

^c Egyptian Petroleum Research Institute (EPRI), Nasr City 11727, Cairo, Egypt

^d Minia Higher Technology Institute for Applied Health Sciences, Minia, P.O. Box 71511, Egypt

^e Botany and Microbiology Department, Faculty of Science, Beni-Suef University, P.O. Box 62511, Egypt

^f Civil Engineering Department, Faculty of Engineering, Suez Canal University, P.O. Box 41522, Ismailia, Egypt

^g Biology Department, Faculty of Education and Arts, Sohar University, Sohar 311, Oman

ARTICLE INFO

Keywords:

Oxidation ponds
Barley straw
Algal blooms
Wastewater treatment
Total suspended solids (TSS)
Dissolved oxygen (DO)
El-Zarabi plant
Eco-friendly wastewater solutions

ABSTRACT

Returning to natural processes has become the central approach in modern wastewater treatment. This study investigates the effectiveness of barley straw (*Hordeum vulgare*) in mitigating algal blooms and reducing total suspended solids (TSS) in maturation basins at the El-Zarabi oxidation pond system in Egypt. Additionally, the study explores barley straw as a sustainable pre-filtration method to enhance sand filtration performance. Laboratory-scale experiments evaluated three placements—surface, suspended, and bottom—using maturation pond effluent with initial concentrations of 182 mg/L COD, 138 mg/L BOD, 86 mg/L TSS, 54 mg/L TN, and 5.2 mg/L TP.

Results monitored over 12 weeks demonstrated that a suspended configuration significantly inhibited algal biomass ($p = 0.0166$) and reduced TSS ($p < 0.05$). While numerical improvements were observed for COD and BOD, the differences were not statistically significant compared to the control ($p > 0.05$). Regarding nutrients, suspended barley straw achieved a statistically significant reduction in Total Nitrogen (TN) from 54 mg/L to <3.4 mg/L ($p = 0.0359$). However, Total Phosphorus (TP) reduction (from 5.2 mg/L to 2.1 mg/L) did not reach statistical significance across all groups. Molecular analyses identified four dominant microalgal species: *Synechocystis* PCC 6803, *Cyanobacterium aponinum*, *Chlorella vulgaris*, and *Desmodesmus intermedius*. The study concludes that barley straw is an effective, low-cost pretreatment that significantly reduces filter clogging and maintenance by managing algal biomass. These findings align with UN Sustainable Development Goals (SDGs 6, 11, 12, and 13). Field-scale validation is recommended to confirm efficacy under diverse operational conditions.

1. Introduction

Wastewater treatment technologies are generally categorized into conventional and non-conventional systems. Conventional systems, such as aerated lagoons, bio-disc rotators, trickling filters, and activated sludge processes, typically require substantial energy inputs. In contrast, non-conventional systems, also referred to as ecotechnologies, primarily rely on natural, organic purification mechanisms. Waste stabilization ponds (WSPs) and constructed wetlands are prominent examples of such

systems, which are particularly recommended for developing countries due to their cost-effectiveness and operational simplicity (Auwah, 2006). Lagoons—also known as stabilization ponds or oxidation ponds—are predominantly utilized in small, rural communities where land is readily available and relatively inexpensive (Bitton, 2011). Oxidation ponds are classified based on the biological activity occurring within them: anaerobic, facultative, and maturation ponds. Typically, a pond system consists of a series of these three pond types arranged in either a sequential or a parallel configuration. Anaerobic and facultative

* Corresponding authors.

E-mail addresses: ashraf.ahmed@brunel.ac.uk (A. Ahmed), abeer_shahawi@eng.suez.edu.eg (A. El Shahawy).

<https://doi.org/10.1016/j.ecoleng.2026.108123>

Received 13 October 2025; Received in revised form 26 July 2026; Accepted 30 July 2026

Available online 19 August 2026

0925-8574/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

ponds are mainly designed for BOD removal, while maturation ponds are primarily intended for pathogen removal.

Nevertheless, some overlap exists: BOD removal occurs in maturation ponds, and pathogen reduction occurs in anaerobic and facultative ponds. Global attention has recently intensified regarding the threats posed by pollution, industrialization, and economic development to water resources. Countries with suitable climatic conditions, including consistently warm temperatures and abundant sunlight, such as Egypt, experience significant algal blooms in maturation ponds. These ponds, characterized by shallow depths and high nutrient loads (Phosphorus and Nitrogen), often facilitate the uncontrolled proliferation of algae. Algal overgrowth can severely affect subsequent sand filtration stages by clogging filters, resulting in operational inefficiencies (Plantier et al., 2013). Although algae are essential components of aquatic ecosystems, they can cause issues when they grow excessively and form blooms. Planktonic algae may turn the water green and murky, whereas filamentous algae can create thick, mat-like layers on the surface. Despite their ecological roles, excessive algal biomass impairs water treatment processes. Algae lack specialized structures such as veins and roots, which distinguishes them from higher plants. Given these challenges, oxidation pond systems often struggle to produce effluent that meets World Health Organization (WHO) (W. H. Organization, 2006) and environmental regulatory standards without tertiary treatment. Sand filtration is commonly employed to reduce residual BOD and TSS concentrations, producing water suitable for environmental discharge or irrigation. The most effective approach for managing algal blooms in maturation ponds involves integrating multiple control strategies. While chemical treatments can be effective, they carry significant ecological risks and should be employed judiciously. Physical and biological methods, including aeration and nutrient management, offer more sustainable, long-term solutions (Murray et al., 2010).

Barley straw has emerged as a natural and cost-effective method for controlling algae. Its mechanism involves the aerobic decomposition of straw, releasing humic and fulvic acids that subsequently form hydrogen peroxide derivatives, inhibiting algal growth (Everall and Lees, 1997) (Balogh, 2008). Unlike herbicides, barley straw selectively targets algae without harming higher aquatic plants or disrupting broader ecological balances. Its application has been successfully demonstrated in various field conditions without documented negative side effects.

In contrast, chemical herbicides often trigger a cascade of environmental problems, including eutrophication, the release of toxic metabolites, and ecosystem disruption. Barley straw's selective, non-toxic mode of action makes it particularly attractive for sustainable wastewater treatment applications (Islami and Filizadeh, 2011; Wren, 2022). Importantly, barley straw does not kill existing algae but prevents the growth of new cells. Its effectiveness is temperature-dependent: in cold waters (<10 °C), activity onset may take six to eight weeks, while in warmer conditions (>20 °C), inhibitory effects may begin within one to two weeks. Despite the ecological advantages of oxidation pond systems, algal blooms remain a critical operational challenge, particularly during maturation. These blooms elevate suspended solids, causing frequent clogging of sand filters used in tertiary treatment.

According to Everall and Lees (1997) and Lembi, (2002), barley straw has been identified as a natural, low-cost material with the potential to inhibit algal proliferation by gradually releasing lignin-derived phenolic compounds during aerobic decomposition. However, its effectiveness under simulated oxidation pond conditions requires systematic investigation. This study hypothesizes that barley straw, particularly when suspended within the water column, can significantly inhibit algal biomass growth and reduce TSS concentrations in maturation ponds. The objective is to evaluate the effect of barley straw placement (surface, suspended, or bottom) on algal growth, TSS, and associated water quality parameters, using laboratory-scale models replicating conditions at El Zarabi Wastewater Treatment Plant. The straw remains active for approximately six months post-application (Diana et al., 2017). Given these properties, the current study

investigates the use of barley straw to inhibit algal growth and reduce TSS concentrations in maturation ponds before tertiary sand filtration at the El-Zarabi wastewater treatment facility.

2. Materials and methods

2.1. El Zarabi treatment plant site

The El-Zarabi Wastewater Treatment Plant is located in El-Zarabi village, Abu Tej District, Assiut, Egypt, at coordinates 26.9761°N, 31.2587°E. The plant operates using a system of natural oxidation lagoons (Fig. 1) and has a design capacity of 16,500 m³ per day. It consists of two sections, each comprising five ponds: an anaerobic pond, a facultative pond, and three maturation ponds (Figure 2S1 (a, b, c, d)). A tertiary sand filter treatment stage is employed downstream of the maturation ponds (Figures 2S1 (c, d)).

2.2. Growth media for algal blooms isolation

The culture medium used was Wuxal Medium (WM), a universal fertilizer (Wilhelm Haug GmbH & Co. KG, Germany), diluted with deionized water (provided by the Botany and Microbiology Laboratory, Beni-Suef University, Egypt). Additional components included sodium alginate (MW = 380,000 g mol⁻¹, 0.1 M; Sigma-Aldrich), Cadmium Sulfate (3CdSO₄·8H₂O, 99%; Oxford Laboratory Reagent, India), and Calcium Chloride (CaCl₂, MW = 110.984 g mol⁻¹, 96%, 0.18 M; Pionchem). Molecular biology reagents included Taq buffer (Ferments, Germany) and a DNA gel extraction kit (Sigma-Aldrich, Germany).

2.3. Isolation and molecular identification of algal blooms

Water samples were manually collected from oxidation tanks and transported to the laboratory for micro-algal isolation. Serial dilution (Schoenborn et al., 2004) was employed to obtain uni-algal cultures by preparing successive dilutions of the water samples. Initial cultivation was performed in Erlenmeyer flasks containing Wuxal medium supplemented with 1% (w/v) NaCl. Cultures were incubated under natural light at a room temperature of 20 °C for two weeks. To purify individual strains, the 13-streak method (Bleeke et al., 2014; Elsayed et al., 2017) was used on solid WM supplemented with 1.5% (w/v) agar, added before autoclaving.

Purification steps were carried out in a controlled-light incubator (CALTECH, RUMED: Rubarth Apparate GmbH, Germany) maintained at 27 ± 1 °C under a 12 h light/12 h dark photoperiod with a light intensity of 105 ± 2 μmol photons m⁻² s⁻¹. After ten days of incubation, distinct colonies were observed. Streaking was repeated as necessary until single, purified colonies were successfully isolated. These colonies were then picked up and sub-cultured in liquid WM for subsequent analyses. Ultimately, four distinct uni-algal species were isolated (Fig. 3).

2.4. Molecular identification of the promised species

Freshly harvested biomass from the fourth isolated microalgal species was mechanically lysed using a bead mill (Retsch MM301, Germany) operated at 30 shakes per second for 20 min. Genomic DNA was then extracted using the DNeasy Plant Mini Kit (Qiagen, Germany) according to the manufacturer's protocol. To identify both eukaryotic and prokaryotic strains, amplification of the 18S rDNA and 16S rDNA regions was carried out using a T3 Thermocycler (Biometra, Göttingen, Germany). The primer pair EukA/EukB was used for targeting eukaryotic sequences, while the primer pair CSIF/ULR (excluding the G-C clamp) was employed for prokaryotic targets (Bleeke et al., 2014; Janse et al., 2003). PCR products were subsequently purified using the QIAquick PCR Purification Kit (Qiagen, Germany). Sanger sequencing was performed by GATC Biotech AG (Konstanz, Germany) (Elsayed et al., 2017).



Fig. 1. The location of El Zarabi Wastewater Treatment Plant, in the Abu Tej District, Assiut, Egypt (Coordinates: 26.9761°N, 31.2587°E).

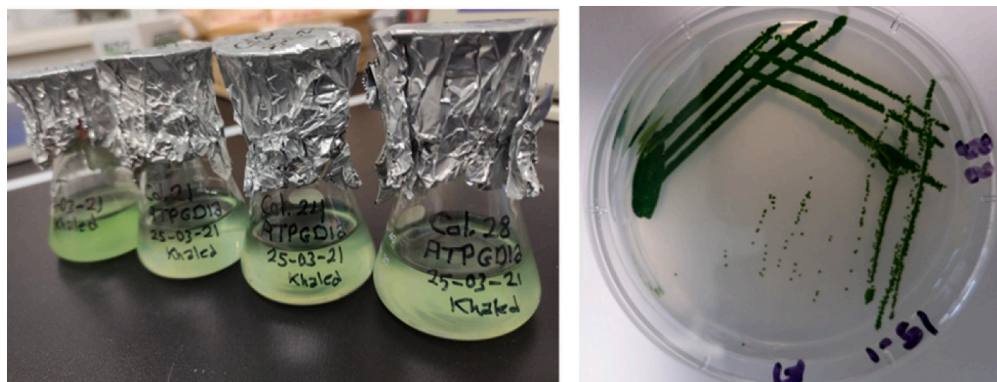


Fig. 3. Isolation and purification of different microalgae species from oxidation tanks on both liquid and solid media containing 0.05% Wuxal. NaCl 1% (w/w) NaCl, maintained at room temperature (20 °C) under ambient natural light of 12 h light/12 h dark photoperiod for ten days.

2.5. Wastewater characteristics

Water samples were stored in 1-l glass bottles, kept in coolers at 4 °C, and transported to the laboratory for analysis within 24 h to prevent any changes in water chemistry. Wastewater quality parameters were analyzed according to the Standard Methods for the Examination of Water and Wastewater, as prescribed by the American Public Health Association (APHA) (A. P. H. Association, 1926). Table 1 summarizes the measured influent parameters.

2.6. Wastewater treatment plant system description and performance

The El-Zarabi wastewater treatment system effectively reduces organic pollutants, suspended solids, and biochemical oxygen demand while promoting nutrient uptake and oxygenation through biological

activity. As illustrated in Table 2S1, the COD decreased from 701 mg/L in the influent to 174 mg/L in the effluent, corresponding to a 75.2% reduction in COD. The most substantial decrease occurred in the anaerobic pond (63.2%), primarily due to anaerobic microbial degradation. BOD levels decreased from 422 mg/L to 137 mg/L (67.5% reduction), with anaerobic and facultative ponds playing a major role in breaking down biodegradable organic matter. TSS decreased from 290 mg/L to 93 mg/L, largely due to sedimentation and microbial activity in the anaerobic and facultative ponds. Slight fluctuations in the maturation ponds are attributed to algal proliferation. DO decreased in the anaerobic pond (3.4 mg/L) but rose in the facultative pond (4.2 mg/L) due to algal photosynthesis. It remained relatively stable across the maturation ponds (3.7–3.9 mg/L). Algal biomass increased significantly from 15 µg/L in the influent to 690 µg/L in the effluent, particularly during the facultative and Maturation stages. This highlights the

Table 1

The influent water quality parameters, including BOD, TSS, COD, DO, chlorophyll-a, TN, and TP, along with the corresponding measurement techniques.

Wastewater quality parameter	Standard Method	Value	Reference
BOD (mg/l)	5 Days of incubation at 20 °C	138	A. P. H. Association, (1926)
Total Suspended Solid(mg/l)	Suspended Solids dried at 103–105 °C	86	
COD (mg/l)	Closed Reflux method (V-730 Double Beam UV-Visible Spectrophotometer)	182	
Dissolved Oxygen (DO) (mg/l)	Hanna Instruments HI9146 Portable Dissolved Oxygen Meter	3.7	
Algal biomass (µg/L)	Chlorophyll a (Trichromatic Method)	705	
Total Nitrogen (mg/l)	Digestion and Photometric Measurement Method	54	
Total Phosphorus (mg/l)	Vanadomolybdophosphoric Acid Colorimetric Method	5.2	

importance of effective algal management to prevent secondary pollution risks, such as eutrophication. Total nitrogen levels exhibited moderate fluctuations across the treatment stages. The influent began at 64 mg/L, increasing to a peak of 73 mg/L in the anaerobic lagoon, likely due to organic nitrogen mineralization and ammonification under anaerobic conditions (Reddy et al., 1984; Reddy et al., 2022). A substantial reduction was observed in the facultative lagoon, to 46 mg/L, as nitrification and algal uptake likely played significant roles. Interestingly, nitrogen levels rose again in Maturation Lagoon 1 (57 mg/L), likely due to microbial decay and nutrient recycling associated with algal biomass turnover. Despite these fluctuations, the effluent nitrogen concentration decreased to 49 mg/L, indicating a net removal efficiency of approximately 23.4%. While moderate, this level may still pose risks for nutrient enrichment in receiving water bodies and calls for further optimization, such as carbon supplementation or biofiltration to enhance denitrification. Total phosphorus concentrations followed a similarly dynamic pattern. The influent phosphorus level was 5.9 mg/L, peaking at 6.2 mg/L in the anaerobic lagoon—a known effect of phosphate release under reducing conditions as iron-bound Phosphorus becomes soluble (Reddy et al., 2022). This was followed by a decline to 5.2 mg/L in the facultative lagoon, with slight fluctuations across the maturation ponds (e.g., 5.3 → 4.9 → 6.1 mg/L). These shifts suggest that while some uptake or sedimentation occurs, phosphorus cycling between algal biomass, microbial action, and sediments may lead to re-release, particularly under high algal biomass conditions. The final effluent phosphorus level (5.2 mg/L) represents a minor reduction of ~11.9%, underscoring the limited phosphorus removal capacity of the current treatment stages. This highlights the need for targeted P-removal strategies, such as chemical precipitation, adsorption media (e.g., iron-coated sand or biochar), or constructed wetlands with P-retentive substrates. The effluent quality was evaluated against WHO standards (W. H. Organization, 2006). Significant deviations were noted, especially for BOD, TSS, TN, TP, and DO, as presented in Table 3S1. These deviations highlight the urgent need for improved tertiary treatment processes, particularly for reducing algal biomass and TSS before sand filtration.

2.7. The experimental system

Raw effluent from the maturation pond was collected and used in laboratory-scale experimental basins (dimensions: 50 cm × 40 cm × 10 cm; volume: 20 L). According to UK Environment Agency (2010), and

Newman and Barrett (1993), the barley straw was prepared by shredding into fragments approximately 5 mm in length, then packed into plastic net containers (mesh size: 3 mm) to ensure uniform exposure to wastewater, with approximately 2 g per pocket. The experimental treatment was achieved by one packet per basin. Three treatment setups were evaluated: Surface Placement (S), where BS nets float at the water surface; Suspended Placement (M), BS nets suspended mid-water column; and Bottom Placement (B), BS nets resting at the bottom of the basin. A control basin without barley straw was also maintained for comparison. Additionally, sand columns (PVC pipes, 30 cm long and 5 cm in diameter) were filled with sorted sandstone (2–3 mm particle size) and overlaid on a plastic net with a 1 mm mesh to give outlet discharge about 30 ml/min with organic loading rate (OLR) 4.54 Kg/m³.d. The treated wastewater, which is effluent from maturation ponds, was passed through a sand column from the top down under gravity to simulate the actual sand filtration in the plant treatment, and it were agreement with (Huisman and Wood, 1974; Tchobanoglous et al., 2014).

2.8. Operating conditions

Basins were stirred daily to simulate natural mixing. Experiments were conducted under ambient sunlight at temperatures ranging from 21 °C to 28 °C. Barley straw decomposition was allowed to occur under aerobic conditions to facilitate the release of inhibitory compounds. The experimental period lasted 12 weeks, during which COD, BOD, TSS, DO, and algal biomass were monitored biweekly. Water samples were collected from multiple randomly selected points across the surface and mid-depth to capture spatial variability. For each sampling event, three independent composite samples were taken per treatment; each composite sample consisted of subsamples pooled from different locations within the basin, thereby minimizing local bias and short-term fluctuations. This approach, which follows common practice in controlled-pond and mesocosm studies, provides independent replicates over time and across space for each treatment level. All samples were analyzed immediately or preserved according to Standard Methods for the Examination of Water and Wastewater to avoid storage artifacts. The combination of (i) controlled operating conditions, (ii) replicated basins, (iii) composite sampling within each basin, and (iv) regular temporal sampling over 12 weeks underpins the validity of the subsequent statistical comparisons among the four treatments (control, surface, suspended, and bottom barley straw).

2.9. Statistical analysis

The effects of the different barley straw placements (surface, suspended, bottom) on water quality parameters (BOD, COD, TSS, DO, chlorophyll-a, TN, and TP) were evaluated using a one-way analysis of variance (ANOVA), with treatment as the fixed factor and the replicate composite samples as independent observations at each sampling time. The validity of the parametric tests was supported by the use of a balanced experimental design ($n = 6$ per group) and composite sampling, which satisfies the assumption of independence and mitigates potential deviations from normality. Furthermore, the assumption of homogeneity of variances was maintained for all ANOVA models, with pooled standard deviations utilized to ensure robust pairwise comparisons via Tukey's HSD test. Where the ANOVA indicated statistically significant differences ($p < 0.05$), Tukey's honestly significant difference (HSD) test was used as a post hoc procedure to identify pairwise differences among treatments. The sampling strategy (stratified composite sampling within each basin and three independent replicates per treatment per sampling event) was designed to provide independent observations that are consistent with the requirements of these statistical tests. All statistical analyses were conducted at a significance level of $\alpha = 0.05$, and results are reported as means with indication of statistically significant differences among treatments where applicable (refer to

supplementary S2).

3. Results & discussion

3.1. Molecular identification and phylogenetic analysis

Prior to DNA extraction, cell lysis was performed using a bead mill at 30 shakes per second for 20 min. However, microscopic examination revealed that the majority of cells remained intact after the initial disruption. Consequently, an additional 20-min lysis step was carried out to ensure complete cell disruption (Janse et al., 2003; Elsayed, 2017).

Genomic DNA was then extracted and subjected to PCR amplification using specific primer pairs. For cyanobacterial identification, the 16S rRNA region was amplified using the CSIF/ULR primer pair (excluding the G-C clamp). At the same time, eukaryotic species were targeted using the 18S rRNA primer pair EukA/EukB (Bleeker et al., 2014; Elsayed et al., 2017). PCR products exhibiting clear, specific bands under UV “illumination” were submitted to GATC Biotech AG for Sanger sequencing (Winckelmann et al., 2015). Post-sequencing, raw chromatograms were processed using various software tools, including Chromas V and MEGA 6. Low-quality regions were trimmed at both ends, and sequences from each primer pair were assembled into contiguous sequences for downstream analysis. The resulting sequences were queried against the NCBI database using BLAST. High similarity matches (up to 99%) with an E-value of 0.00 were obtained for several strains, including *Synechocystis* sp. PCC 6803. Phylogenetic analysis identified the fourth isolated algal blooms as comprising two cyanobacterial strains—*Synechocystis* PCC 6803 and *Cyanobacterium aponinum*—and two chlorophyta (green algae) strains—*Chlorella vulgaris* and *Desmodesmus intermedius* (See Supplementary Data (S₃) for alignment and tree details).

3.2. Analysis of water quality parameters in maturation basins

In oxidation ponds for wastewater treatment, particularly those with aeration (maturation ponds), algal blooms offer few benefits and pose various problems, such as elevated BOD and TSS levels. Biological oxygen demand is also correlated (Diana et al., 2017; Boylan and Morris, 2003).

Algae are primarily responsible for TSS in pond effluent, and levels can exceed the amount of input. The increased oxygen demand of the receiving waterway is the cause of the effluent's elevated TSS levels. The current study focused on the finished product of the oxidation ponds, which is the water of the maturation ponds. Maturation pond water is considered the influent for the tertiary treatment (sand filters). The characteristics of the maturation pond water contents are illustrated in Table 3, which makes it reasonable to have the contents for the COD, BOD, and DO parameters. Still, it had a high algal mass and TSS ratio, making this water unsuitable for entering sand filters and causing them to clog. Generally, the results are inconsistent as to which types of algae are managed. However, there is some encouraging anecdotal and scientific evidence that barley straw helps suppress at least some algae species. Barley straw generally clears green water caused by algae and effectively suppresses planktonic algae. This finding may be consistent with (Fervier et al., 2020), who reported that Cyanobacteria concentration was strongly influenced by both the incubation period and the treatment. In contrast, filamentous algae development on artificial macrophytes was significantly affected by incubation time but not by treatment.

However, data on its management of filamentous algae, mat-forming algae, and blue-green algae are conflicting (Murray et al., 2010; Madsen and Wersal, 2017). The four cases of barley straw were compared to enhance maturation pond effluents in terms of BOD, COD, TSS, TN, TP, algal mass, and DO parameters before entering the tertiary treatment process over 12 weeks (Table 4a S1, Table 4b S1).

Heterotrophic bacteria and algae play complex and often intertwined

roles in the cycling of phosphorus (P) and Nitrogen (N) nutrients in aquatic ecosystems. Algae, as primary producers, utilize inorganic forms of Nitrogen and Phosphorus, while heterotrophic bacteria primarily consume organic forms of these nutrients. Factors such as nutrient availability, light, and dissolved organic matter influence these interactions. In wastewater treated in oxidation ponds, heterotrophic bacteria and algae have a symbiotic relationship in the nutrient cycle. Heterotrophic bacteria depend on the oxygen produced by algae through the photosynthesis process to digest organic matter and decompose it into primary inorganic elements, such as Phosphorus and Nitrogen, which are essential nutrients for algae to bloom and grow (Boylan and Morris, 2003; Świerk et al., 2025; Lim et al., 2015; Pęczuła, 2013; Ó hUallacháin and Fenton, 2010; Ferrier et al., 2005; Ball et al., 2001). Therefore, when the BS action reduced algal levels, heterotrophic bacteria and dissolved oxygen (DO) levels also decreased, as shown in Tables 4S1.

3.2.1. Effect of BS on BOD and COD levels

Biochemical oxygen demand (BOD) is a key indicator of organic pollution in water and wastewater, reflecting the oxygen required by microorganisms to decompose organic material (Nguyen et al., 2022). Similarly, chemical oxygen demand (COD) measures the amount of oxygen required to oxidize both biodegradable and non-biodegradable organic compounds. At the initial stage, all experimental setups exhibited high BOD and COD concentrations, indicating substantial organic loads. Over time, BOD and COD levels declined in all conditions, indicating progressive degradation of organic matter. However, the reduction rates differed among treatments. Control Basin showed the fastest decrease in BOD and COD levels, reaching the lowest concentrations by the final weeks. This is attributed to accelerated microbial decomposition in the absence of algal inhibition effects. In basins treated with BS, reductions in BOD and COD occurred more gradually. Among BS treatments, the suspended barley straw (M) condition showed slightly better degradation trends than the surface (S) or bottom (B) placements. Figs. 4 and 5 illustrate the trends in BOD and COD across all treatments. The slower BOD and COD reduction observed in BS-treated basins may be attributed to the gradual release of phenolic compounds during straw decomposition, which could temporarily increase organic loads before enhancing microbial activity (Everall and Lees, 1996). The suspended BS placement (M) provided more uniform oxygenation and greater interaction with wastewater, thereby optimizing degradation rates.

Despite these trends, paired *t*-tests and Tukey HSD tests confirmed no statistically significant differences in final BOD and COD levels among the treatment groups (Figures 6S1–9S1).

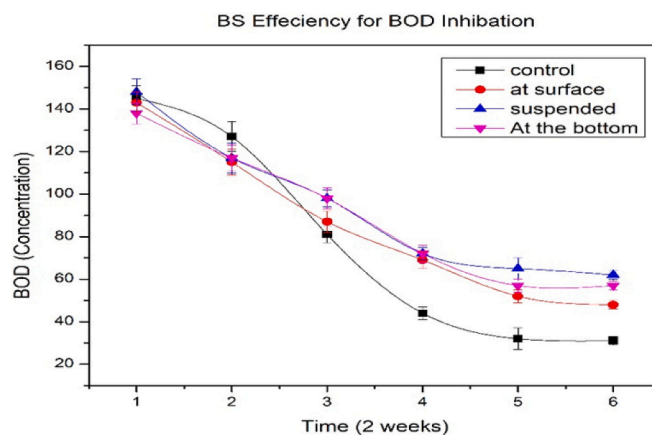


Fig. 4. BOD concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

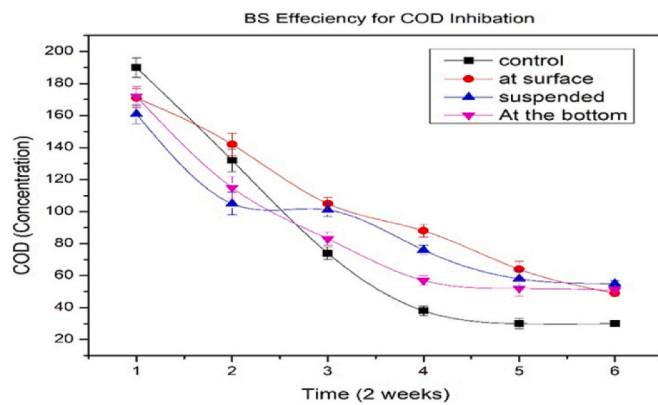


Fig. 5. COD concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

3.2.2. Effect of BS on Algae biomass

Algal biomass (as indicated by chlorophyll *a* concentration) showed distinct patterns among treatments over the experimental period (Fig. 10): Control Basin: Algal biomass increased exponentially, reaching approximately 750 $\mu\text{g/L}$ by the end of the study. Surface (S) and Bottom (B) Treatments: Moderate inhibition of algal growth was observed. Suspended (M) Treatment: Demonstrated the strongest inhibition, maintaining consistently low algal biomass levels ($\sim 100 \mu\text{g/L}$). Suspended BS facilitated better interaction with algal cells and more uniform distribution of inhibitory compounds within the water column. These findings are consistent with previous studies (Murray et al., 2010; Madsen and Wersal, 2017), which suggest that the position of barley straw is critical to its algal control efficacy. Paired *t*-tests and Tukey HSD analyses confirmed that Algal_M (suspended treatment) significantly inhibited algal biomass compared to other setups ($p = 0.0166$).

The inhibition effect of barley straw on algal blooming is interpreted as due to the lignin materials released from decayed barley straw, which increase with an increased contact time of straw with treated wastewater (Pęczuła, 2013; Ridge and Pillinger, 1996). Lignin, a major structural component found in plant stems and seed heads, is considered the primary source of phenolic acids and quinones. These bioactive compounds are released during the degradation (rotting) process. Several researchers have emphasized that lignin breakdown—and the subsequent release of these compounds—is the principal factor responsible for barley's algicidal activity. Moreover, phenolic compounds extracted from *Myriophyllum spicatum* via methanolic extraction

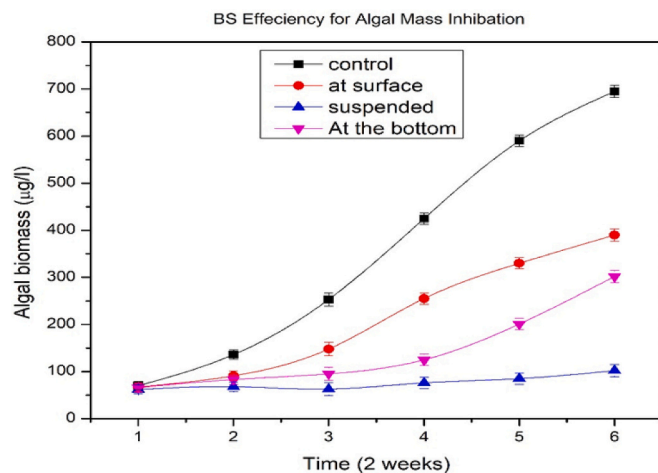


Fig. 10. Algal mass concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

have been shown to inhibit the growth of cyanobacteria and algal species such as *Anacystis nidulans* and *Selenastrum capricornutum* (Boylan and Morris, 2003; Świerk et al., 2025; Pęczuła, 2013; Ó hUallacháin and Fenton, 2010; Ball et al., 2001). Algal_M is the most effective treatment for inhibiting algal biomass growth, as confirmed by both the *t*-test and Tukey HSD ($p = 0.0166$). Other treatments (Algal_B and Algal_S) do not show significant differences in algae inhibition compared to Algal_C (Figure 11S1, Figure 12S1).

3.2.3. Effect of BS on DO

Dissolved oxygen (DO) is a critical parameter for assessing the biological health of secondary wastewater treatment processes. It reflects the amount of oxygen available for microbial degradation of organic materials in both raw and treated wastewater, and compliance with WHO standards is essential for safe discharge of effluent into natural water bodies. In maturation ponds, algal photosynthesis contributes to DO production during daylight hours, but respiration at night and algal die-offs can deplete oxygen levels, creating hypoxic conditions (Hasan et al., 2023; Wurtsbaugh et al., 2019; Li et al., 2022).

The experimental results showed distinct DO trends across the treatments: Suspended Barley Straw (DOM): Achieved the highest and most consistent DO increase, reaching approximately 6.5 mg/L by the end of the experimental period. Surface Barley Straw (DOS): Demonstrated a moderate DO increase, stabilizing around 5.0 mg/L. Bottom Barley Straw (DOB): Exhibited a slight DO rise, fluctuating between 4.0 and 4.5 mg/L, suggesting slower oxygenation. Control Basin (DOC): Showed minimal DO improvement over time, indicating limited natural oxygen diffusion in the absence of barley straw. The significantly higher DO concentrations observed under the suspended barley straw condition (DOM) suggest that this configuration enhanced water column aeration and mixing. The suspended barley straw likely created microenvironments that supported both oxygen production (through controlled algal activity) and oxygen retention (through reduced algal respiration stress). In contrast, the surface and bottom treatments offered less consistent oxygenation benefits, potentially due to stratification effects and limited interaction with the full water column (Fig. 13). The control basin's limited DO increase highlights the inadequacy of passive diffusion alone in maintaining optimal oxygen levels in stagnant waters. This finding aligns with previous studies emphasizing the need for active mixing or biological interventions to sustain oxygenation in maturation ponds (Hasan et al., 2023). Paired *t*-tests and Tukey HSD tests were conducted to assess differences among treatments. Although most comparisons showed no statistically significant differences ($p > 0.05$), the DOC vs. DOM comparison revealed a significant difference in DO concentrations ($p < 0.05$), confirming the superior performance of the suspended barley straw treatment. Figure 14S1. Paired *T*-Test results

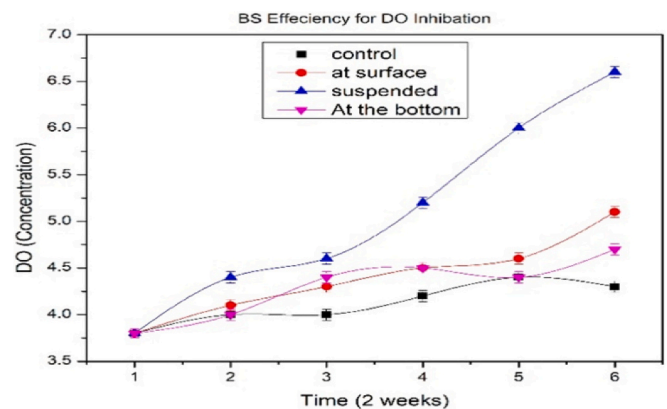


Fig. 13. Dissolved Oxygen (DO) concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

showing p -values for DO comparisons. As shown in Figure 15S1, the Tukey HSD plot illustrates confidence intervals; only the DOC vs. DOM confidence interval does not cross the zero line. Maintaining higher DO concentrations is crucial not only for organic matter decomposition but also for inhibiting anaerobic conditions that can lead to odour generation, pathogen persistence, and the release of nutrients (e.g., ammonia, phosphorus) from sediments. These results suggest that applying suspended barley straw could improve overall pond resilience and effluent quality by promoting more stable oxygen dynamics.

3.2.4. Effect of BS on TSS

High levels of TSS in wastewater lagoons, particularly those with aeration, pose significant challenges to treatment efficiency and environmental compliance. Algal blooms are a major contributor to TSS and associated BOD, with each milligram of algal biomass contributing approximately 0.5 mg of BOD (Ekunke and Nzereogu, n.d.; Anderson et al., 2017; Gallardo-Rodríguez et al., 2019). Elevated TSS and BOD levels increase the oxygen demand of receiving waterways, exacerbating eutrophication risks. The experimental results showed distinct differences in TSS trends among treatments: Control Basin (TSSC): Displayed a continuous rise in TSS concentrations, reaching approximately 190 mg/L by the end of the study, indicating ongoing algal proliferation and particulate accumulation.

Surface (TSSS) and Bottom (TSSB) Treatments: Exhibited moderate TSS increases, stabilizing between 100 and 120 mg/L. Suspended Treatment (TSSM): Demonstrated a significant decrease in TSS, reaching approximately 30 mg/L by the final measurement. As shown in Fig. 16, the trends in TSS concentration across treatments over the experimental period are illustrated.

The continuous rise in TSS in the control basin confirms that algal biomass is a primary driver of suspended solids in maturation ponds. Without intervention, algae growth can cause effluent TSS levels to exceed influent values, consistent with findings reported by (Butler et al., 2017). The significant reduction in TSS under the suspended barley straw condition (TSSM) suggests that multiple interacting mechanisms are at play. Algal Bloom Inhibition: Barley straw decomposition releases bioactive phenolic compounds that inhibit algal proliferation (Pillinger et al., 1994), thereby limiting the biological contribution to TSS. Enhanced Particulate Settling: Suspended barley straw may facilitate microbial biofilm development, thereby promoting the aggregation and sedimentation of fine particulates. Improved Oxygenation: Higher DO levels observed under suspended BS conditions likely support aerobic microbial processes that stabilize organic particulates. Surface and bottom placements of barley straw (TSSS and TSSB) were less effective, possibly due to reduced interaction with the full

water column and uneven distribution of inhibitory compounds. These findings underscore the importance of treatment placement in maximizing barley straw effectiveness. Paired t -tests and Tukey HSD tests confirmed that TSSM treatment significantly reduced suspended solids compared to all other treatments ($p < 0.05$). No statistically significant differences were found among the TSSC, TSSS, and TSSB treatments, suggesting comparable performance across these groups. Figures 17S1 and 18S1. Paired t -test p -values and Tukey HSD analysis for TSS comparisons. These statistical outcomes reinforce the superior performance of suspended barley straw application in controlling TSS.

Effective control of TSS is critical for maintaining the performance of downstream sand filtration systems and ensuring compliance with effluent quality standards. By reducing TSS and associated organic loads, suspended barley straw treatment can prolong filter operational life, reduce maintenance requirements, and mitigate secondary pollution risks.

Furthermore, TSS management through natural means, such as barley straw application, supports sustainable wastewater treatment strategies by minimizing the need for chemical coagulants.

3.2.5. Effect of BS on TN and TP

Fig. 19 illustrates the temporal trends in Total Nitrogen (TN) concentrations over twelve weeks across four treatment configurations: Control, Surface, Suspended, and Bottom barley straw (BS) placements. The Suspended BS treatment showed the most pronounced reduction in TN, dropping from 54 mg/L at week 0 to below 3.4 mg/L by week 6, well below the reference TN discharge limit (≈ 15 mg/L). In comparison, the Control group exhibited a slower decline, reaching only ~ 28 mg/L by week 6. Both Surface and Bottom BS placements followed intermediate trajectories, achieving ~ 21 – 23 mg/L by the end of the study period. The Suspended BS consistently outperformed all other treatments throughout the experiment. The observed reduction in TN under suspended barley straw conditions suggests a synergistic effect of straw decomposition and microbial activity, particularly enhanced denitrification in oxygen-limited microzones (Butler et al., 2017; Butler et al., 2001). The suspended position likely created favourable redox conditions that promoted the anaerobic transformation of nitrate to nitrogen gas, a key mechanism in natural nitrogen removal (Knowles, 1982; Zheng et al., 2013). The lower performance of surface and bottom placements can be attributed to suboptimal contact between decomposing straw and microbial biofilms, or to less stable environmental niches for denitrifiers. Similar findings have been reported, showing that organic carbon from barley straw can stimulate heterotrophic denitrifiers in aquaculture and wastewater systems (Newcomer et al., 2012; Scott et al., 2020). The control group's limited TN removal highlights the insufficiency of passive pond processes alone to meet regulatory nitrogen thresholds.

In contrast, the Suspended BS treatment reduced TN below the environmental discharge limit, demonstrating its potential as a cost-effective, biodegradable alternative for decentralized wastewater treatment systems (Metcalf et al., 2014; Goyne, 2021). The superior performance of Suspended BS in reducing TN supports the concept of organic carbon-driven denitrification. Barley straw serves as a carbon substrate, enhancing denitrifying microbial activity in anaerobic microzones, which leads to substantial nitrate removal, as documented in drainage bioreactor studies (e.g., ~ 63 – 70% nitrate reduction). The suspended configuration likely optimizes the straw's surface area, fostering biofilm formation and facilitating electron donor-acceptor interactions. Fig. 20 illustrates the change in Total Phosphorus (TP) concentrations over a twelve-week period under four treatments: Control, Surface, Suspended, and Bottom barley straw (BS) placements. All treatments showed a gradual reduction in TP levels. The Suspended BS treatment achieved the greatest reduction, from 5.2 mg/L to 2.1 mg/L. Control, surface, and Bottom placements converged at ~ 4.2 – 4.4 mg/L by week 6. Only Suspended BS approached the TP limit threshold (~ 3.0 mg/L), suggesting some phosphorus mitigation potential. Unlike its

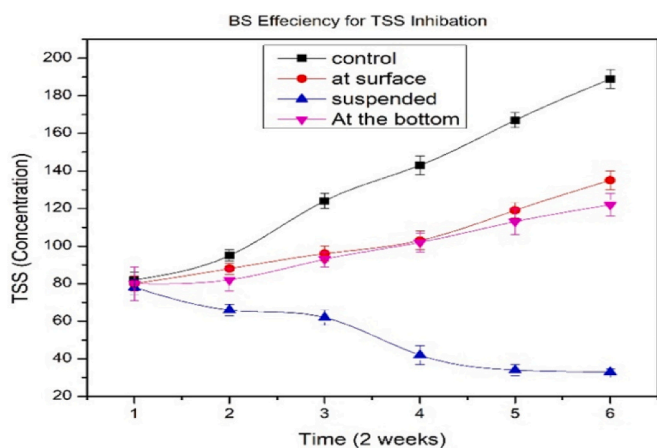


Fig. 16. Total Suspended Solids (TSS) concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

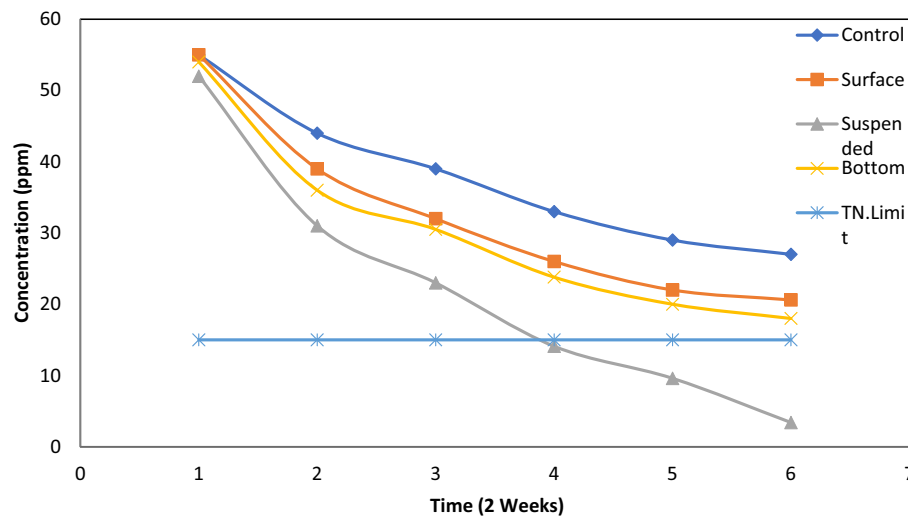


Fig. 19. Total Nitrogen (TN) concentrations over the twelve-week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

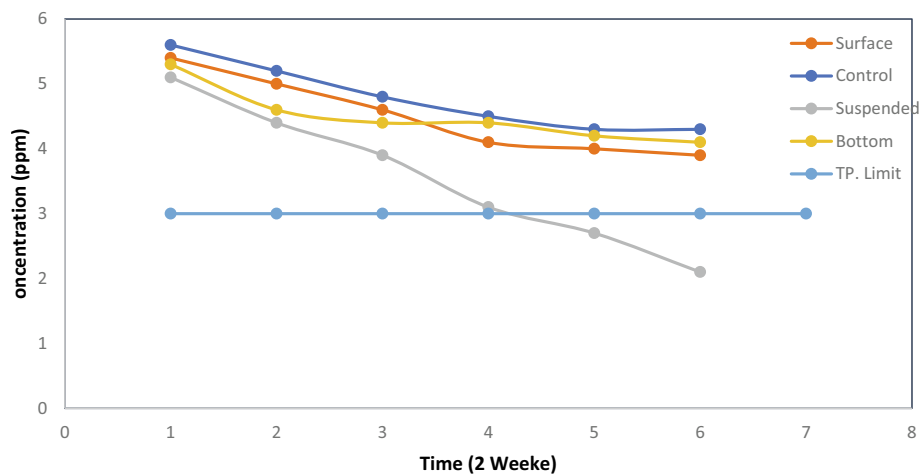


Fig. 20. Total Phosphorus (TP) concentrations over the twelve week experimental period under different barley straw treatments at (Control, Surface, Suspended, and Bottom).

strong influence on Nitrogen, barley straw's impact on Phosphorus was less pronounced and more variable. The modest reduction in TP observed in the Suspended BS treatment may be attributed to: Microbial uptake during straw decomposition, which can temporarily immobilize P in biomass (Søndergaard et al., 2003). Formation of iron-phosphate complexes, promoted by reducing conditions created during anaerobic decomposition of straw (Kadlec and Wallace, 2008). However, such mechanisms are typically slow and sensitive to environmental pH and redox fluctuations, which may explain the limited TP removal under other placements (Surface, Bottom). The control and most barley straw placements hovered near 4.3 mg/L throughout, suggesting limited phosphorus attenuation from natural pond processes alone. Only the suspended treatment showed a notable downward trend, indicating the suspended mode enhances retention time and surface area, potentially fostering biofilm-driven phosphorus sorption and uptake. Similar results were reported by (Butler et al., 2001), who found that barley straw slightly reduced TP in aquatic systems but was significantly more effective at controlling algae and nitrogen.

Additionally, Sadasivam (Sadasivam, 2009) demonstrated that low-cost media like wood chips or straw provide limited phosphorus retention, and that effective TP removal often requires metal-based substrates or chemical precipitation. While barley straw, especially in a suspended

configuration, exhibits some capacity to reduce Phosphorus, it remains inefficient as a standalone TP removal strategy. The results suggest its best utility is in combined systems, where it targets Nitrogen and algal biomass, while other components (e.g., iron, alum, or biochar-based filters) address phosphorus loads.

Barley straw (BS), particularly in its suspended placement, demonstrated a notable capacity to reduce Total Nitrogen (TN) in wastewater maturation basins. Over a twelve-week experimental period, nitrogen concentrations dropped significantly faster under suspended BS compared to control and other BS placements. This supports the hypothesis that barley straw promotes microbial or chemical pathways that enhance nitrogen transformation or uptake. In contrast, Total Phosphorus (TP) levels showed a gradual, though less pronounced, reduction across all treatments. While the suspended BS still performed better than the control, the rate and extent of phosphorus removal were lower, indicating a potentially different mode or limitation of action for phosphorus mitigation. Paired *t*-tests revealed a statistically significant difference in TP reduction between Control and Suspended BS ($p = 0.044$), and a near-significant trend for TN ($p = 0.097$). Tukey HSD post hoc analysis showed that TN reduction between the Control and Suspended BS groups was statistically significant ($p = 0.0359$), whereas no significant differences in TP were detected across groups. Boxplots and

heatmaps visually reinforced that Suspended BS consistently had the lowest median concentrations of both TN and TP; however, the TN reduction was statistically significant. The findings suggest that suspended barley straw can serve as a natural, sustainable enhancement to maturation basins, facilitating nitrogen removal without requiring chemical dosing or mechanical aeration. Its minimal cost, low maintenance, and biodegradable nature make it particularly attractive for rural or resource-limited settings.

However, since TP reductions were less consistent and not statistically significant, barley straw alone may not be sufficient for phosphorus control and may need to be paired with other treatment technologies (e.g., chemical precipitation, constructed wetlands) in systems with strict P discharge limits.

The comparison between Control and Suspended BS was statistically significant ($p = 0.0359$), with a clear reduction in TN under the Suspended BS treatment. All other pairwise comparisons (e.g., Control vs Bottom, Surface vs Suspended) were not statistically significant ($p > 0.05$), although Suspended BS generally showed the lowest mean TN values. No statistically significant differences were detected among any pair of treatments (all p -values > 0.05). While Suspended BS showed numerically lower TP levels, the variability among groups prevented these differences from reaching statistical significance.

The Tukey plots visually confirmed these findings: for TN (Fig. 21S1), the confidence interval for Control vs Suspended did not cross zero, indicating significance. In contrast, all TP intervals intersected zero, showing non-significant results. The significant difference between Control and Suspended BS for TN removal underscores the enhanced efficiency of the suspended configuration. The suspended straw likely provides a greater surface area for microbial colonization, especially by denitrifiers. Improved contact with water and biofilms, facilitating carbon release and nitrate reduction. This aligns with studies showing that barley straw enhances heterotrophic denitrification when properly submerged or suspended (Haller et al., 2018). The lack of significant differences for TP (Fig. 22S1) suggests that barley straw, while useful for Nitrogen, is not a reliable phosphorus removal agent. TP reduction mechanisms, such as microbial uptake and complexation with iron or calcium, are slower and less consistent in aquatic conditions without chemical enhancement (Ravichandran and Philip, n.d.). Suspended BS is a promising low-cost strategy for enhancing TN removal in maturation basins and natural treatment systems. However, TP removal will likely require complementary technologies, such as chemical dosing (e.g., alum) or engineered media (e.g., biochar, steel slag). The Tukey HSD analysis confirms that Suspended Barley Straw significantly improves nitrogen removal, whereas phosphorus mitigation is not statistically different across treatments. This underscores the need for integrated nutrient management strategies in wastewater treatment, particularly in systems that rely on natural or passive processes.

The Total Nitrogen (TN) paired t -test heatmap (Fig. 23S1) reveals the statistical relationship between different barley straw treatments in terms of nitrogen removal. Among the comparisons, the Control vs. Suspended pair shows the lowest p -value (0.097), suggesting a near-significant difference. Although this does not meet the conventional 0.05 threshold, it aligns with observed trends showing more effective TN reduction under the Suspended configuration. Other comparisons, such as Control vs. Surface and Surface vs. Bottom, show much higher p -values (≥ 0.28), indicating no statistically significant difference in TN removal between the treatments.

In contrast, the Total Phosphorus (TP) heatmap (Fig. 24S1) reveals a clearer statistical pattern. The Control vs. Suspended comparison produces a statistically significant result ($p = 0.044$), indicating that Suspended barley straw is effective in reducing phosphorus concentrations compared to no treatment. While other pairwise comparisons, such as Surface vs. Bottom or Control vs. Bottom, show lower p -values than TN, they remain above the 0.05 threshold and are therefore not statistically significant. This suggests that only the Suspended configuration provides a measurable improvement in phosphorus removal, reinforcing its

potential as a natural treatment method for dual nutrient control.

3.3. Differentiated roles of Barley Straw in nitrogen and phosphorus reduction

Barley straw (BS) plays a role in nutrient management in aquatic systems, but its effects on Nitrogen (N) and Phosphorus (P) differ fundamentally. For Nitrogen, BS primarily serves as a carbon source that supports microbial denitrification. When submerged in wastewater, the decomposing straw releases organic carbon, which supports denitrifying bacteria that convert nitrate (NO_3^-) into nitrogen gas (N_2), thereby removing it from the system. While BS does not directly adsorb significant amounts of Nitrogen, its indirect contribution through microbial activity makes it effective in nitrogen reduction. In this study, a modest increase in nitrogen content—from 0.043 wt% to 0.094 wt%—was observed in BS before and after use, supporting its involvement in nitrogen cycling processes. However, the amount of straw applied (5 g per 20 L) was relatively low compared to recommended doses (up to 10 g/L) that yield more pronounced microbial activity and nutrient attenuation (Carricondo Anton et al., 2020; Ma et al., 2011).

In contrast, raw BS has a limited capacity to remove Phosphorus from wastewater. Phosphorus typically requires chemical or physical binding for removal, which raw BS lacks due to its low surface area and insufficient reactive sites (Gallardo-Rodríguez et al., 2019). Studies have shown that barley straw ash—produced by combustion—contains more effective phosphate-binding components and has demonstrated greater phosphate adsorption capacity (Carricondo Anton et al., 2020). In the current study, phosphorus content in BS increased from 0.025 wt% to 0.18 wt% after application, suggesting an interaction, possibly via weak adsorption or accumulation. However, without chemical modification (e.g., acid treatment to increase carboxyl groups), raw BS remains largely ineffective for substantial phosphorus removal, and its use in this context should be considered minimal unless enhanced by pretreatment or conversion to ash (Carricondo Anton et al., 2020).

Despite differences in nitrogen and phosphorus removal pathways, BS suppresses algal blooms through a distinct mechanism: the release of natural algistatic compounds during slow microbial decomposition. As BS breaks down over several weeks, it generates low concentrations of hydrogen peroxide (H_2O_2) and phenolic compounds that selectively inhibit the growth of algae, especially cyanobacteria (also known as blue-green algae), without harming fish or beneficial aquatic plants (Murray et al., 2010; Pillinger et al., 1994). These compounds disrupt algal metabolism and limit bloom formation when applied preventively. To be effective, BS should be deployed before bloom onset, ideally in early spring. Straw is typically floated in mesh bags near the water surface, where oxygen supports decomposition. The inhibitory effects emerge within 1–2 weeks in warm conditions (above 20 °C) and take 6–8 weeks in cooler water, providing a gradual, ecologically safe means of controlling algal blooms.

4. Discussion

The results indicate that suspending barley straw in the maturation pond water column significantly inhibited algal biomass growth and reduced TSS concentrations. This effect is likely mediated by the gradual release of phenolic compounds and hydrogen peroxide derivatives during aerobic decomposition of the straw, as previously suggested by (Everall and Lees, 1997). These bioactive compounds may inhibit key physiological processes in algae, such as photosynthesis and cell division, thereby reducing algal proliferation. Furthermore, the mid-column placement of barley straw appears critical; suspended placement maximizes interaction with planktonic algal cells and optimizes the diffusion of inhibitory agents throughout the water body, thereby minimizing vertical stratification effects.

In addition to algal control, the improvement in dissolved oxygen (DO) concentrations observed in the suspended straw treatment likely

results from a reduction in algal respiration demands and enhanced microbial aerobic activity, aligning with previous findings by Wurtsbaugh et al. (Wurtsbaugh et al., 2019). However, the limited impact on COD and BOD suggests that while barley straw effectively suppresses biological oxygen demand associated with algal biomass, it does not substantially enhance overall organic matter degradation. This suggests the need for combined treatment strategies, such as barley straw application coupled with low-energy mechanical aeration or nutrient reduction interventions, to achieve broader wastewater polishing objectives.

Importantly, these laboratory-scale findings must be interpreted cautiously. Factors such as fluctuating pond temperatures, variable algal species dynamics, and hydrodynamic mixing in full-scale systems may modulate the efficacy of barley straw. Therefore, field-scale validation under different climatic and operational conditions is strongly recommended before widespread implementation. Future studies should also investigate the potential impact of barley straw on nutrient cycling, particularly phosphorus dynamics, given the close relationship between phosphorus availability and algal bloom intensity (Mosley et al., 2022).

4.1. The flow efficiency by sand filters before and after using BS as a Pre-filtration

In this research section, a practical laboratory simulation study is conducted to determine the influence of Barley Straw on wastewater in oxidation pond maturation basins, aiming to remove algae and TSS before they enter the sand filters, thereby achieving tertiary treatment.

4.1.1. The flow efficiency by sand filters before using BS as a Pre-filtration

When maturation pond effluent, untreated with barley straw, was fed directly into sand filtration units, frequent backwash cycles were required to maintain operational performance. As shown in Fig. 25, untreated wastewater, characterized by elevated algal biomass and TSS, resulted in rapid clogging of the sand media. This condition necessitated backwashing approximately four times more frequently than systems pretreated with barley straw.

The high algal load contributed to the accumulation of organic films and biofouling within the sand bed, thereby increasing head loss and impairing filtration efficiency. This operational challenge not only increases maintenance costs but also reduces the effective lifespan of sand filtration systems, and it agreement with Tchobanoglous et al. (2014)

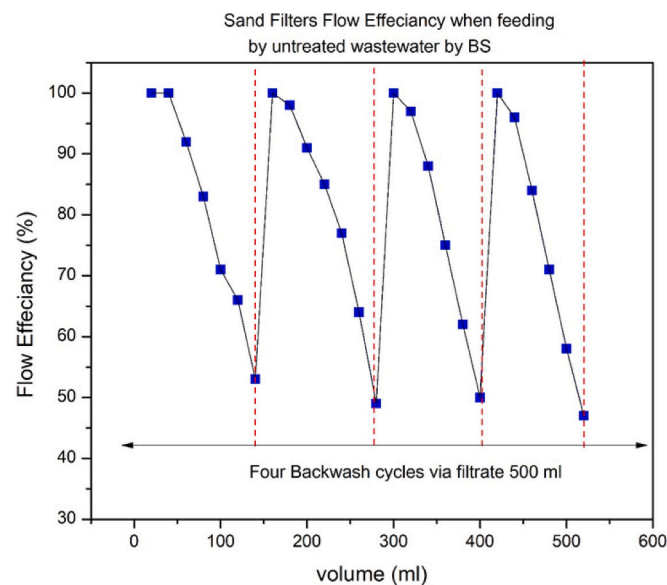


Fig. 25. The frequency of backwashes for sand filters without BS treatment in the influent wastewater.

and Huisman and Wood (1974).

4.1.2. The flow efficiency by sand filters after using BS as a pre-filtration

Barley straw treatment significantly improved sand filter performance by reducing both algal biomass and TSS concentrations in the influent. It is essential to note that BS flotation at the wastewater surface cannot reduce light penetration, as light intensity is a factor in algal bloom proliferation. The experimental basins (dimensions: 50 cm × 40 cm), but the Barley straw (BS) was prepared by shredding it into fragments approximately 5 mm in length, then packed into plastic net containers (mesh size: 3 mm), and the packet dimensions: 4 cm × 3 cm, so it will be covered very small area (Table 5) when was compared with the surface of the experimental basins and in addition the atmosphere of upper Egypt (the location of the experiments conduction) is highly sunny so the sun light continues stay in the day for time interval reached about 16 h.

Barley straw contains a high proportion of lignin, a complex and relatively recalcitrant polymer. As the straw decomposes under aerobic aquatic conditions, fungi and bacteria gradually break down lignin, releasing a range of phenolic and quinone-like compounds. Formation of inhibitory phenolic intermediates. Partial lignin oxidation produces low-molecular-weight phenolics (e.g., simple phenols, aldehydes, and quinones) and hydrogen peroxide (H₂O₂). These compounds are known to: Interfere with algal photosynthesis (particularly photosystem II), disrupt cell membrane integrity, and inhibit enzyme activity involved in algal growth and metabolism. This explanation agrees with what was reported by Everall and Lees (1996) and Newman (1997); Everall and Lees (1997); Balogh (2008); Everall and Lees (1996); Welch et al. (1990)). According to Tchobanoglous et al. (2014) and Huisman and Wood, 1974, barley straw indirectly reduces the organic and particulate loads that contribute to filter clogging by suppressing algal proliferation. With fewer algae and suspended solids, particulate accumulation in the sand bed was minimized, as reflected by the lower backwashing frequency (Fig. 26). Reduced solids allowed water to pass through the filter media more consistently, maintaining higher flow rates. With less organic fouling, the sand filter maintained its structural integrity and filtration efficiency over a longer operational period (Fig. 18). Reduced backwashing frequency for sand filters after barley straw treatment of maturation pond effluent.

The observed improvements in sand filter operation following barley straw treatment can be attributed to a dual-action mechanism:

- Algal Inhibition: Reduced algal biomass decreases organic matter deposition and minimizes the formation of algal biofilms, which are a primary cause of filter clogging.
- TSS Reduction: Lower concentrations of fine suspended particles result in less physical blockage within the sand media.

These effects collectively create a more stable filtration environment, preventing rapid headloss development and reducing operational disruptions. This synergistic benefit is consistent with prior studies, which indicate that natural organic treatments can improve filtration processes by enhancing water clarity and reducing biological fouling (Murray et al., 2010; Wren, 2022).

Table 5

The dimensions of the barley straw pocket (X x Y x L) and the corresponding sun exposure times at different hours of the day, indicating light exposure during the experimental period.

Time (h)	Dimensions of BS Pocket XxYxL (cm)
6 am	3.4 × 4.5 × 1.9
10 am	3 × 4 × 1.3
12 pm	3 × 4 × 1
3 pm	3 × 4.1 × 1.4
5 pm	3.5 × 4.6 × 1.9
7 pm	4.1 × 5.3 × 2.3

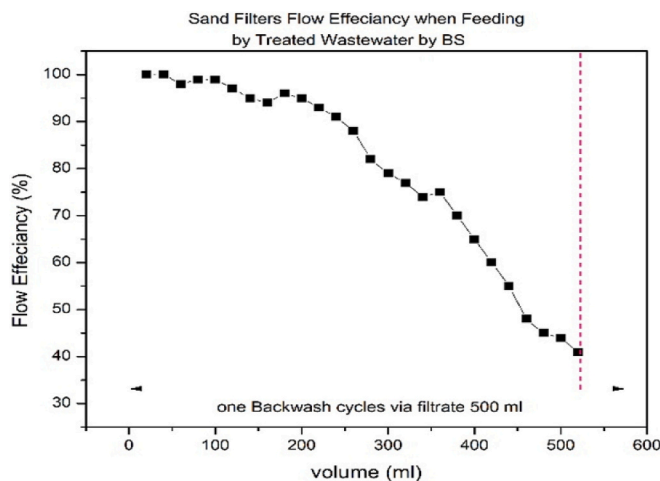


Fig. 26. The effect of BS on the reduction of the number of backwashes of the sand filters.

Incorporating barley straw as a pre-filtration step in oxidation pond systems provides a sustainable and cost-effective approach to enhancing the performance and longevity of sand filtration units. This method reduces the operational burden associated with frequent backwashing and minimizes chemical usage for algae control. Given the pressing need for low-energy, eco-friendly solutions in decentralized wastewater treatment, barley straw presents a viable alternative to chemical algicides and mechanical aerators, and it was in agreement with Harriman R., R., Adamson, K., & Lowe, S. (1997).

Therefore, field-scale validation is necessary to reduce algal blooms and total suspended solids (TSS) and improve the efficiency of sand-filter flow, especially since the laboratory study showed that applying barley straw as a pretreatment stage produced a highly improved effect. After sand filter stages, the wastewater quality was assessed according to WHO standards (W. H. Organization, 2006). All parameters were found to be within the permissible limits, as shown in Table 6S1 (refer to supplementary S1).

5. Conclusion

This study explored the application of barley straw (*Hordeum vulgare*) to inhibit algal blooms and reduce total suspended solids (TSS) in maturation ponds at the El-Zarabi wastewater treatment facility. Laboratory-scale experiments demonstrated that suspending barley straw within the water column was the most effective strategy for enhancing water quality parameters. The phylogenetic analysis of the isolated strains confirmed their classification into two primary micro-algal groups: blue-green algae and green algae. Suspended barley straw (TSSM) significantly reduced TSS levels compared to surface (TSSS), bottom (TSSB), and control (TSSC) treatments, with p -values < 0.05 indicating statistical significance. The suspended barley straw condition also achieved the highest dissolved oxygen (DO) concentrations over time, likely due to enhanced aeration and mixing. Algal biomass inhibition was most effective under the suspended treatment (Algal M), as confirmed by both paired t -tests and Tukey HSD tests ($p = 0.0166$). No significant impact on BOD and COD removal was observed between BS-treated and control basins, indicating that barley straw mainly influences algal-related parameters rather than organic matter breakdown directly. Barley straw pretreatment improved the operational efficiency of downstream sand filtration units by reducing filter clogging and extending the interval between backwash events. The effectiveness of barley straw appears to be linked to the release of phenolic compounds during aerobic decomposition, which inhibits algal growth while promoting the settling of particulates. However, this study was limited to laboratory-scale conditions under controlled temperatures and light

exposure. Therefore, field-scale validation is necessary to confirm the reproducibility of these findings under varying environmental and operational conditions.

Barley straw offers a sustainable, low-cost, and eco-friendly alternative to chemical algicides in oxidation pond systems, particularly in settings where land availability and climatic conditions favor natural treatment processes.

5.1. Recommended study for application

Based on the promising results of this study, a practical model for real-world implementation is proposed. The recommended design integrates suspended barley straw units directly into the maturation pond stages before tertiary sand filtration. Fig. 27 illustrates the proposed physical model for integrating barley straw treatment in oxidation pond systems. This model involves strategically suspending barley straw bundles at mid-depths in maturation ponds to maximize their inhibitory effect on algal blooms. Scheduling barley straw applications in autumn, winter, or early spring, where straw decomposition can initiate at lower temperatures and become active within 4–6 weeks. Replacing barley straw every six months to maintain inhibitory efficacy, particularly before the peak algal blooming seasons, and monitoring critical parameters, including DO, TSS, algal biomass, and nutrient concentrations, to optimize treatment effectiveness and sand filter performance.

5.2. Future research directions and limitations

While this study provides significant evidence for the efficacy of barley straw as a natural algal inhibitor and wastewater conditioner, several limitations must be acknowledged to ensure a balanced interpretation of the results:

Laboratory-Scale Constraints: All experiments were conducted under controlled laboratory conditions in 20 L basins. The decomposition dynamics and inhibitory effects of barley straw may vary significantly in full-scale operational facilities due to factors such as hydrodynamic mixing, fluctuating nutrient loads, and seasonal temperature extremes. Consequently, extrapolation to operational wastewater treatment plants must be done with caution.

Indirect Mechanistic Evidence: The study attributes algal inhibition to the release of lignin-derived phenolic compounds and hydrogen peroxide during aerobic straw decomposition. However, these bioactive intermediates were not directly measured or quantified chemically; their presence and role are inferred based on the observed biological responses and established literature.

Inefficiency in Phosphorus Removal: While barley straw was highly effective for nitrogen reduction, it proved inefficient as a stand-alone strategy for phosphorus removal. Statistical analysis (Tukey HSD) confirmed that TP reduction was not significant across all groups, likely because raw straw lacks the reactive binding sites required for substantial phosphorus adsorption.

Simplified Filtration Model: The sand filtration experiment was a practical laboratory simulation using small columns and sorted sand-stone. This model does not fully capture the complexities of large-scale sand filters, such as variable hydraulic loading and the multi-layered depth dynamics of industrial-scale systems.

Requirement for Field-Scale Validation: Because the study was conducted in controlled 20 L laboratory basins, field trials are necessary to confirm that the results can be reproduced under the complex conditions of operational facilities, such as the El-Zarabi plant.

Addressing Technical Gaps: Future work must move beyond biological observation to direct chemical monitoring of inhibitory compounds (like phenolics and peroxide). Furthermore, since raw barley straw proved inefficient for significant phosphorus removal, research should focus on integrated systems that combine straw with metal-based substrates like iron or alum.

Optimization of Operational Strategies: Proposed research

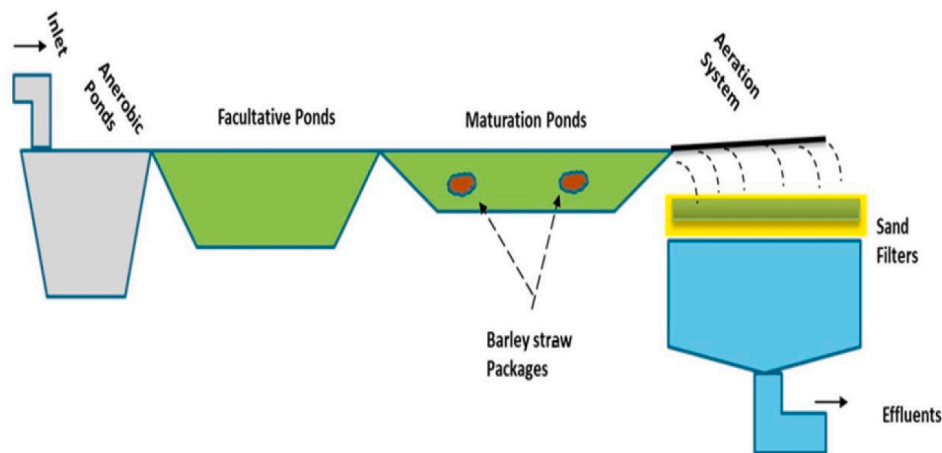


Fig. 27. This physical model with the recommended method in the oxidation ponds system using a Barley Straw as a tertiary treatment system.

directions include investigating optimal loading rates and placement strategies, studying the interaction of straw with nutrient cycling (ammonia, nitrate, and phosphate), and exploring the synergistic effects of combining barley straw with mechanical aeration.

Acknowledgment of Laboratory Limitations: The study acknowledges that its findings are based on controlled temperatures (21 °C to 28 °C) and consistent light exposure, which do not capture the hydrodynamic variability, temperature extremes, or fluctuating nutrient loads found in real-world maturation ponds.

CRediT authorship contribution statement

Atef Mohamed Gad Mohamed: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ashraf Ahmed:** Writing – review & editing, Supervision. **Eman A. Mahmoud:** Writing – review & editing, Methodology, Investigation. **Eman M. Farahat:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Khaled N.M. Elsayed:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Abeer El Shahawy:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors thank **Eng. Mostafa El Shemi**, the Head of the Holding Company for Water and Wastewater, and **Prof. Dr. Salah Bayoumi**, Vice Head of the Holding Company, and **Eng. Mahmoud Shehata Mohamed**, the Head of the Assiut and New Valley Company for Water and Wastewater, for their continuous support of the Research and Development Team. Special thanks to Dr. Yasser Youssef and Dr. Mai Sadek; they are responsible for the Research and Development Sector at the Holding Company, and special thanks to the Head of the Planning Sector and the members of the Planning Sector at the Assiut and New Valley Company for Water and Wastewater for supporting our team's research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2026.108123>.

[org/10.1016/j.ecoleng.2026.108123](https://doi.org/10.1016/j.ecoleng.2026.108123).

Data availability

The data that has been used is confidential.

References

- A. P. H. Association, 1926. Standard methods for the Examination of Water and Wastewater. American public health association.
- Anderson, C.R., Sellner, K.G., Anderson, D.M., 2017. Bloom Prevention and Control. <https://doi.org/10.25607/OBP-312>.
- Awuah, E., 2006. Pathogen Removal Mechanisms in Macrophyte and Algal Waste Stabilization Ponds. Wageningen University and Research. <https://edepot.wur.nl/32925>.
- Ball, A.S., Williams, M., Vincent, D., Robinson, J., 2001. Algal growth control by a barley straw extract. *Bioresour. Technol.* 77 (2), 177–181. [https://doi.org/10.1016/S0960-8524\(00\)00148-6](https://doi.org/10.1016/S0960-8524(00)00148-6).
- Balogh, L., 2008. Himalayan balsam, *Impatiens glandulifera* 2008, 129–137.
- Bitton, G., 2011. Wastewater Microbiology. John Wiley & Sons. <https://doi.org/10.1002/9780470901243>.
- Bleeke, F., Rwehumbiza, V.M., Winckelmann, D., Klöck, G., 2014. Isolation and characterization of new temperature tolerant microalgal strains for biomass production. *Energies* 7 (12), 7847–7856. <https://doi.org/10.3390/en7127847>.
- Boylan, J.D., Morris, J.E., 2003. Limited effects of barley straw on algae and zooplankton in a midwestern pond. *Lake and Reservoir Management* 19 (3), 265–271. <https://doi.org/10.1080/07438140309354091>.
- Butler, B., Terlizzi, D., Ferrier, D., 2001. "Barley Straw: A Potential Method of Algae Control in Ponds," *Water Quality Workbook Series*. Maryland Sea Grant Extension Program. University of Maryland College Park, Maryland, USA.
- Butler, E., Hung, Y.-T., Al Ahmad, M., Suleiman, Yeh, R.Y.-L., Liu, R.L.-H., Fu, Y.-P., 2017. Oxidation pond for municipal wastewater treatment. *Appl. Water Sci.* 7 (1), 31–51. <https://doi.org/10.1007/s13201-015-0285-z>.
- Carricondo Anton, J.M., Oliver-Villanueva, J.V., Turégano Pastor, J.V., Raigón Jiménez, M.D., González Romero, J.A., Mengual Cuquerella, J., 2020. Reduction of phosphorus from wastewater through adsorption processes reusing wood and straw ash produced in bioenergy facilities. *Water Air Soil Pollut.* 231 (3), 128. <https://doi.org/10.1007/s11270-020-04502-4>.
- Diana, J.S., Szyper, J.P., Batterson, T.R., Boyd, C.E., Piedrahita, R.H., 2017. Water quality in ponds. In: *Dynamics of pond aquaculture*, pp. 53–71.
- O. V. Ekunke and K. Nzereogu, "Advancing the Use of Marine Algae as a Carbon Sink and Bio-fuel Source in Offshore Oil and Gas Operations".
- Elsayed, K., 2017. "Production of Biofuels from Microalgae," *IRC-Library, Information Resource Center der Jacobs University Bremen Bremen*
- Elsayed, K.N., Kolesnikova, T.A., Noke, A., Klöck, G., 2017. Imaging the accumulated intracellular microalgal lipids as a response to temperature stress. *3 Biotech* 7 (1), 41. <https://doi.org/10.1016/j.biombioe.2011.04.021>.
- UK Environment Agency. (2010). Barley straw for algae control in water bodies (Environment Agency guidance document).
- Everall, N., Lees, D., 1996. The use of barley-straw to control general and blue-green algal growth in a Derbyshire reservoir. *Water Res.* 30 (2), 269–276. [https://doi.org/10.1016/0043-1354\(95\)00192-1](https://doi.org/10.1016/0043-1354(95)00192-1).
- Everall, N.C., Lees, D.R., 1997. The identification and significance of chemicals released from decomposing barley straw during reservoir algal control. *Water Res.* 31 (3), 614–620. [https://doi.org/10.1016/S0043-1354\(96\)00291-6](https://doi.org/10.1016/S0043-1354(96)00291-6).
- Ferrier, M., Butler Sr., B., Terlizzi, D., Lacouture, R., 2005. The effects of barley straw (*Hordeum vulgare*) on the growth of freshwater algae. *Bioresour. Technol.* 96 (16), 1788–1795. <https://doi.org/10.1016/j.biortech.2005.01.021>.

- Fervier, V., Urrutia-Cordero, P., Piano, E., Bona, F., Persson, K.M., Hansson, L.-A., 2020. Evaluating nutrient reduction, grazing and barley straw as measures against algal growth. *Wetlands* 40 (1), 193–202. <https://doi.org/10.1007/s13157-019-01167-6>.
- Gallardo-Rodríguez, J.J., Astuya-Villalón, A., Llanos-Rivera, A., Avello-Fontalba, V., Ulloa-Jofré, V., 2019. A critical review on control methods for harmful algal blooms. *Rev. Aquac.* 11 (3), 661–684. <https://doi.org/10.1111/raq.12251>.
- Goyne, L., 2021. Cyanobacteria Blooms and Water Quality Parameters in Two Mecklenburg County Park and Recreation Ponds in Charlotte, NC. North Carolina State University. <https://repository.lib.ncsu.edu/items/707c41b8-6da1-44df-b887-b18ae0d98d5e>.
- Haller, H., Jonsson, A., Romero, M.L., Pascua, M.J., 2018. Bioaccumulation and translocation of field-weathered toxaphene and other persistent organic pollutants in three cultivars of amaranth (a. cruentus' R127 México', A. Cruentus 'Don León' y a. caudatus' CAC 48 Perú')—a field study from former cotton fields in Chinandega, Nicaragua. *Ecol. Eng.* 121, 65–71. <https://doi.org/10.1016/j.ecoleng.2017.07.019>.
- Hasan, B.R., Islam, M.S., Kundu, P., Mallick, U.K., 2023. Modeling the effects of algal bloom on dissolved oxygen in eutrophic water bodies. *Journal of Mathematics* 2023 (1), 2335570. <https://doi.org/10.1155/2023/2335570>.
- Huisman, L., Wood, W.E., 1974. Slow sand filtration. *World Health Organization*.
- Islami, H.R., Filizadeh, Y., 2011. Use of barley straw to control nuisance freshwater algae. *J. Am. Water Works Ass.* 103 (5), 111–118. <https://doi.org/10.1002/j.1551-8833.2011.tb11458.x>.
- Janse, I., Meima, M., Kardinaal, W.E.A., Zwart, G., 2003. High-resolution differentiation of cyanobacteria by using rRNA-internal transcribed spacer denaturing gradient gel electrophoresis. *Appl. Environ. Microbiol.* 69 (11), 6634–6643. <https://doi.org/10.1128/AEM.69.11.6634-6643.2003>.
- Kadlec, R.H., Wallace, S., 2008. *Treatment Wetlands*. CRC Press. <https://doi.org/10.1201/9781420012514>.
- Knowles, R., 1982. Denitrification. *Microbiol. Rev.* 46 (1), 43–70. doi:0146-0749/82/010043-28\$02.00/0.
- Lembi, C.A., 2002. Barley straw for algae control. *Aquatic Plant Management Report APM-1-W*. Purdue University Cooperative Extension Service, West Lafayette.
- Li, M., et al., 2022. The significance of phosphorus in algae growth and the subsequent ecological response of consumers. *J. Freshw. Ecol.* 37 (1), 57–69. <https://doi.org/10.1080/02705060.2021.2014365>.
- Lim, B., et al., 2015. Application of barley straw to dammed river for algal control. *Desalin. Water Treat.* 54 (13), 3728–3736. <https://doi.org/10.1080/19443994.2014.923195>.
- Ma, Z., et al., 2011. Adsorption removal of ammonium and phosphate from water by fertilizer controlled release agent prepared from wheat straw. *Chem. Eng. J.* 171 (3), 1209–1217. <https://doi.org/10.1016/j.cej.2011.05.027>.
- Madsen, J.D., Wersal, R.M., 2017. A review of aquatic plant monitoring and assessment methods. *J. Aquat. Plant Manag.* 55 (1), 1–12.
- Metcalfe, et al., 2014. *Wastewater Engineering: Treatment and Resource Recovery*. McGraw Hill Education.
- Mosley, L., et al., 2022. A Scientific Evaluation to Inform Nutrient Removal Options for the Coorong. Goyder Institute for Water Research Technical Report Series, no. 22/06.
- Murray, D., Jefferson, B., Jarvis, P., Parsons, S., 2010. Inhibition of three algae species using chemicals released from barley straw. *Environ. Technol.* 31 (4), 455–466. <https://doi.org/10.1080/09593331003663294>.
- Newcomer, T.A., et al., 2012. Influence of natural and novel organic carbon sources on denitrification in forest, degraded urban, and restored streams. *Ecological monographs* 82 (4), 449–466. <https://doi.org/10.1890/12-0458.1>.
- Newman, J.R., Barrett, P.R.F., 1993. Control of *Microcystis aeruginosa* by decomposing barley straw. *J. Aquat. Plant Manag.* 31 (1).
- Newman, J. (1997). Control of algae with barley straw (Centre for Aquatic Plant Management, Information Sheet No. 1). Centre for Ecology and Hydrology.
- Nguyen, L.N., et al., 2022. Nutrient removal by algae-based wastewater treatment. *Curr. Pollut. Rep.* 8 (4), 369–383. <https://doi.org/10.1007/s40726-022-00230-x>.
- Ó hUallacháin, D., Fenton, O., 2010. Barley (*Hordeum vulgare*)-induced growth inhibition of algae: a review. *J. Appl. Phycol.* 22 (5), 651–658. <https://doi.org/10.1007/s10811-009-9492-z>.
- Pęczuła, W., 2013. Influence of barley straw (*Hordeum vulgare* L.) extract on phytoplankton dominated by *Scenedesmus* species in laboratory conditions: the importance of the extraction duration. *Journal of Applied Phycology* 25 (2), 661–665. <https://doi.org/10.1007/s10811-012-9900-7>.
- Pillinger, J., Cooper, J., Ridge, I., 1994. Role of phenolic compounds in the antialgal activity of barley straw. *J. Chem. Ecol.* 20 (7), 1557–1569. <https://doi.org/10.1007/BF02059880>.
- Pillinger, J.M., Cooper, J.A., Ridge, I., 1994. Role of phenolic compounds in the antialgal activity of barley straw. *J. Chem. Ecol.* 20 (7), 1557–1569.
- Plantier, S., Castaing, J.-B., Sabiri, N.-E., Masse, A., Jaouen, P., Ponté, M., 2013. Performance of a sand filter in removal of algal bloom for SWRO pretreatment. *Desalination and Water Treatment* 51 (7–9), 1838–1846. <https://doi.org/10.1080/19443994.2012.699336>.
- M. K. Ravichandran and L. Philip, "Insight into the Role of Substrate Materials, Plant, and Microbes in the Removal of Pharmaceutically Active Compounds Through Laboratory-Scale Constructed Wetland Studies," Plant, and Microbes in the Removal of Pharmaceutically Active Compounds Through Laboratory-Scale Constructed Wetland Studies. doi:<https://doi.org/10.2139/ssrn.3983772>.
- Reddy, K., Patrick, W., Broadbent, F., 1984. Nitrogen transformations and loss in flooded soils and sediments. *Crit. Rev. Environ. Sci. Technol.* 13 (4), 273–309. <https://doi.org/10.1080/10643388409381709>.
- Reddy, K.R., DeLaune, R.D., Inglett, P.W., 2022. *Biogeochemistry of wetlands: science and applications*. CRC press. <https://doi.org/10.1201/9780429155833>.
- Ridge, I., Pillinger, J., 1996. Towards understanding the nature of algal inhibitors from barley straw. *Hydrobiologia* 340 (1), 301–305. <https://doi.org/10.1007/BF00012772>.
- Sadasivam, B.Y., 2009. Phosphorus Removal from Wastewater Using Greensand Media. Tennessee Technological University. <https://globethesis.com/?t=2441390002985098>.
- Schoenborn, L., Yates, P.S., Grinton, B.E., Hugenholtz, P., Janssen, P.H., 2004. Liquid serial dilution is inferior to solid media for isolation of cultures representative of the phylum-level diversity of soil bacteria. *Appl. Environ. Microbiol.* 70 (7), 4363–4366. <https://doi.org/10.1128/AEM.70.7.4363-4366.2004>.
- Scott, B., Baldwin, A.H., Ballantine, K., Palmer, M., Yarwood, S., 2020. The role of organic amendments in wetland restorations. *Restor. Ecol.* 28 (4), 776–784. <https://doi.org/10.1111/rec.13179>.
- Søndergaard, M., Jensen, J.P., Jeppesen, E., 2003. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* 506 (1), 135–145. <https://doi.org/10.1023/B:HYDR.0000008611.12704.dd>.
- Świerk, D., et al., 2025. The influence of active metabolites from the decomposition of camelina and barley straw on the development of phytoplankton from eutrophic freshwater ecosystem. *Sci. Rep.* 15 (1), 305. <https://doi.org/10.1038/s41598-024-82343-5>.
- Tchobanoglous, G., Stensel, H.D., Tsuchihashi, R., Burton, F.L., Abu-Orf, M., Bowden, G., Pfrang, W., 2014. *Wastewater engineering: Treatment and resource recovery*, 5th ed. McGraw-Hill Education.
- W. H. Organization, 2006. Guidelines for the Safe Use of Wastewater, Excreta and Greywater. World Health Organization. <https://www.who.int/publication/s/i/item/9241546832>.
- Welch, I.M., et al., 1990. Barley straw as an inhibitor of algal growth I: studies in the Chesterfield Canal. *J. Appl. Phycol.* 2 (3), 231–239.
- Winkelmann, D., Bleeke, F., Bergmann, P., Klöck, B., 2015. Growth of *Cyanobacterium aponinum* influenced by increasing salt concentrations and temperature. *3 Biotech* 5 (3), 253–260. <https://doi.org/10.1007/s13205-014-0224-y>.
- Wren, H., 2022. Allelopathic Effect of Cereal Straw Extracts on Growth of *Raphidocelis subcapitata* and *Microcystis aeruginosa*. University of Arkansas.
- Wurtsbaugh, W.A., Paerl, H.W., Dodds, W.K., 2019. Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *Wiley Interdiscip. Rev.: Water* 6 (5), e1373. <https://doi.org/10.1002/wat2.1373>.
- Zheng, C., Zhao, L., Zhou, X., Fu, Z., Li, A., 2013. Treatment Technologies for Organic Wastewater. In: *Water Treatment*. IntechOpen. <https://doi.org/10.5772/52665>.