Research Article **Rev. Cong. Sci. Technol., Vol. 5, No. 2, pp. 821-833 (2026)**

OPEN ACCESS

Revue Congolaise des Sciences & Technologies

ISSN: 2959-202X (Online); 2960-2629 (Print)

https://www.csnrdc.net/

REVUE CONGOLAISE DES SCIENCES ET TECHNOLOGIES

Development of Bioplastic Films from *Schizothrix lacustris* Reinforced with Corn Cob Cellulosic Fibers

[Développement de films de bioplastique à partir de *Schizothrix lacustris* renforcés par des fibres cellulosiques de la rafle de maïs]

Arsène Kayeye Muabu[1,2], Esther Malundama Biolo[1], Ismael Kabuya Mulumba[1,2], Naomie Mpandu Bolangongo[1,2], Christiane Nsende Ngoyi[3], Theodore Kashishi Kazadi[1,2], Hercule Mulonda Kalele[1], Pierre Osomba Lohohola[1], Taba Muzele Kalulu[1,2] & Joséphine Kankolongo Ntumba[1,2*]

[1]Department of Chemistry, Faculty of Science and Technology, University of Kinshasa, BP 190, Kinshasa XI, Congo DR

.[2]Organic Chemistry and Energy Laboratory, Faculty of Science and Technology, University of Kinshasa, BP 190, Kinshasa XI, Congo DR

.[3]Department of Sciences Environment, Faculty of Sciences, University of Kinshasa, Kinshasa, Democratic Republic of Congo

Abstract

The global dependence on conventional petroleum-based plastics is leading to a massive accumulation of non-biodegradable waste and exacerbating climate change. In this context, bioplastics represent a sustainable alternative. This study explores the production of bioplastic films from cyanobacterial biomass belonging to the genus Schizothrix, collected in the ponds of Maluku (Kinshasa, DRC), reinforced with cellulosic fibers extracted from maize cobs. Cyanobacterial glycogen was isolated after pretreatment, whereas the lignocellulosic fibers were obtained by alkaline delignification and bleaching. The films were made by casting/evaporation with different glycogen/fibre ratios. Physicochemical and functional analyses (drying time, thickness, water content, water retention, combustion and biodegradability) show that the incorporation of fibers improves mechanical strength, reduces hydrophilicity and accelerates drying. The yields obtained (glycogen: 66,03 ± 0,28 %; fibres: 48,17 ± 0,33 %) confirm the potential of these local biomasses to be used as raw materials for biodegradable bioplastics. This approach is a promising way to develop Congolese resources and reduce plastic pollution. Thus, this study makes an original contribution to the Congolese context by linking local data to global trends.

Keywords: biofilms, bioplastics, cyanobacterium, biodegradable, DRC

Résumé

La dépendance mondiale aux plastiques conventionnels à base de pétrole conduit à une accumulation massive de déchets non biodégradables et aggrave le changement climatique. Dans ce contexte, les bioplastiques représentent une alternative durable. Cette étude explore la production de films bioplastiques à partir de biomasse cyanobactérienne appartenant au genre Schizothrix, collectés dans les étangs de Maluku (Kinshasa, RDC), renforcés avec des fibres cellulosiques extraites des épis de maïs. Le glycogène cyanobactérien a été isolé après prétraitement, tandis que les fibres lignocellulosiques ont été obtenues par délignification alcaline et blanchiment. Les films étaient réalisés par coulée/évaporation avec différents rapports glycogène/fibres. Les analyses physicochimiques et fonctionnelles (temps de séchage, épaisseur, teneur en eau, rétention d'eau, combustion et biodégradabilité) montrent que l'incorporation de fibres améliore la résistance mécanique, réduit l'hydrophilie et accélère le séchage. Les rendements obtenus (glycogène : 66,03 ± 0,28 % ; fibres : 48,17 ± 0,33 %) confirment le potentiel de ces biomasses locales à être utilisées comme matières premières pour des bioplastiques biodégradables. Cette approche est une manière prometteuse de développer les ressources congolaises et de réduire la pollution plastique. Ainsi, cette étude apporte une contribution originale au contexte congolais en reliant les données locales aux tendances mondiales.

Mots clés : biofilms, bioplastiques, cyanobactérie, biodégradable, RDC

*Auteur correspondant : Joséphine Kankolongo Ntumba, (josephine.ntumba@unikin.ac.cd). Tél. : (+243) 854704596

https://orcid.org/0009-0005-2343- 2310; Reçu le 10/04/2026 ; Révisé le 07/05/2026 ; Accepté le 29/05/2026

DOI : https://doi.org/10.59228/rcst.026.v5.i2.288

1. Introduction

According to the OECD, global plastics production doubled between 2000 and 2019, from 234 million tons to nearly 460 million tons. Yet, only 9% of these materials were recycled and 12% incinerated, leaving the majority to accumulate in landfills or disperse into the environment. Due to their non-biodegradable nature, conventional plastics persist for centuries, depending on polymer composition and environmental conditions, while releasing greenhouse gases that accentuate climate change (Babaremu et al., 2022; OECD, 2023).

The Democratic Republic of Congo, like many developing countries, is no exception to this problem. Its capital, Kinshasa, generates more than 7,800 tons of waste, or about 237 kilos per capita each year (Kang et al., 2023). This accumulation illustrates the urgency of finding sustainable alternatives to petroleum-based plastics (Mavula et al., 2024).

In this context, bioplastics appear to be a promising solution. Produced from renewable biomass, they have several advantages: reduced greenhouse gas emissions, faster decomposition and lower energy consumption during recycling (Sharma et al., 2025; Piao et al., 2024). Among the various sources of biomass, algae stand out for their considerable potential in green chemistry and the design of innovative biomaterials (Sarker & Kaparaju, 2025; Kumar et al., 2026).

However, glycogenated bioplastics suffer from certain limitations, including their hydrophilicity and low mechanical properties, which compromise their stability. The incorporation of cellulosic fibers into a glycogen matrix of cyanobacterial origin could be an effective strategy to overcome these limitations. Agricultural waste such as maize cobs is an abundant and undervalued source of cellulosic fibres, which can improve the mechanical properties of bioplastics (Dewan et al., 2024; Alam et al., 2024).

The hypothesis of this study is that the addition of cellulosic fibers extracted from corn cobs to a bioplastic based on the glycogen of the cyanobacterium *Schizothrix lacustris* significantly improves its physico-mechanical properties (reduction of hydrophilicity, increase of mechanical strength, acceleration of drying) while maintaining satisfactory biodegradability.

2. Material and methods

2.1 Harvesting, storage

Cyanobacteria were sampled in the Maluku ponds, at the Mutambwe and Nganda Musoko sites (figure 1), which sites were chosen for their ecological conditions favorable to the development of cyanobacteria and microalgae. The first site is laid out as ponds, while the second is associated with market gardening, each fed by a narrow stream. The transparency of the water allowed direct observation of the colonies, facilitating manual harvesting. The samples were stored in 30 cL plastic bottles to preserve their integrity before laboratory analysis (Moreno Osorio et al., 2021; Wang & Hong, 2022).

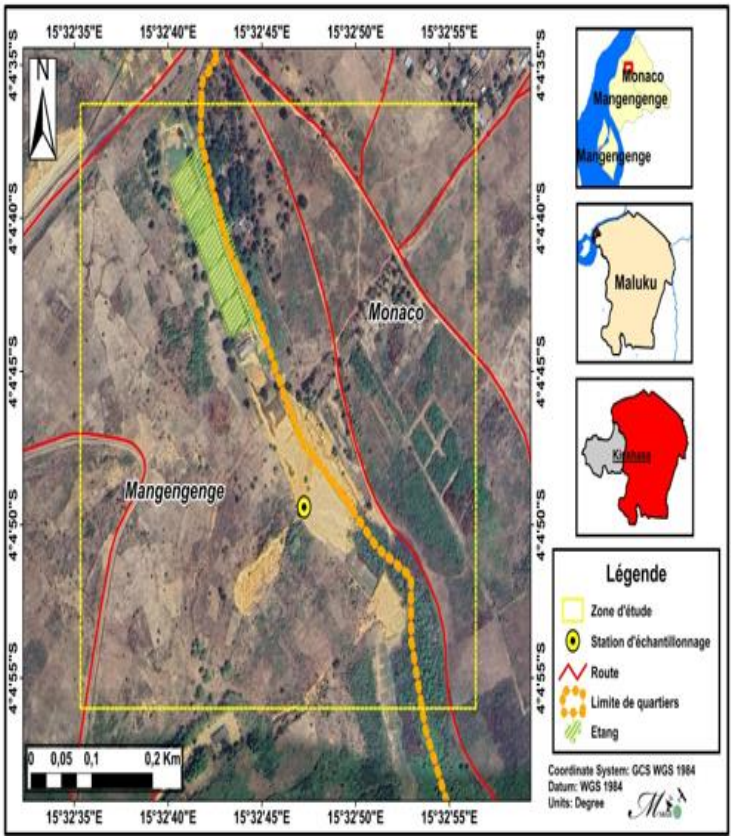

Figure 1: Geographical map of the cyanobacteria harvesting site (Maluku Ponds)

2.2 Sample Review, Identification and Analysis

The examination of the samples was carried out at the Hydrobiology, Limnology and Aquaculture Laboratory of the Faculty of Science and Technology (room C-34) of the University of Kinshasa, according to the protocol established by the said laboratory. The observations were made under a MOTIC (Swift line) optical microscope with a magnification of 100×.

A subsample was slide-placed and observed at objective 10×10 and identified using taxonomic keys. Two samples (E1 and E2) were collected and observed, allowing the genus *Schizothrix lacustris* to be retained for further experiments, due to its easy recognition and abundance on the site (Guiry & Guiry, 2023).

In order to characterize the growing conditions, some physicochemical parameters of the water were measured in situ on the Mutambwe and Nganda Musoko streams: salinity, pH, total dissolved solids (TDS), temperature and conductivity. The measurements were carried out using a multiparameter, after washing the electrode with distilled water and preparing the 120 mL beaker. These field analyses have made it possible to better understand the trophic environment of cyanobacteria (Moreno et al., 2021).

Cyanobacterial biomass was characterized by three standardized methods. The moisture content was determined by drying at 105 °C in accordance with ISO 712:2009. The ash content was measured by calcination at 550 °C in accordance with ISO-5984:2009. Finally, the presence of glycogen was demonstrated by a qualitative test with Lugol, whose change in colour confirms the presence of polysaccharides.

2.3 Pretreatment and Glycogen Extraction

A massive harvest was carried out at the Mutambwe site. Fresh seaweed was collected in transparent containers, washed several times with tap water, and then distilled to remove impurities. After mechanical drying and 7 hours of solar exposure, they were crushed at 32,000 rpm for 2 minutes. The resulting powder was stored in airtight containers. This protocol is in line with recent practices for the preparation of cyanobacterial biomass for biofilms and biotechnological valorization (Zhang et al., 2023).

Glycogen extraction was carried out using a method adapted from De Porcellinis (2017): 500 g of powder was mixed with 2000 mL of ethanol, heated in a water bath at 40 °C for 2 hours, and then filtered. The residues were kiln-dried at 50°C to a constant weight. The glycogen granules obtained in this way were preserved for later uses. This approach illustrates the growing interest in exploiting cyanobacteria as a source of functional polysaccharides (Wang & Hong, 2022).

2.4 Lugol test

Lugol's solution is prepared by dissolving 2 g of KI in 100 mL of distilled water and then adding 1 g of crystalline iodine. The complexation reaction between molecular iodine and iodide ions allows the formation of a color complex, which is used to reveal the presence of glycogen.

Upon application, the appearance of a black discolouration indicates a positive result (+), confirming the presence of glycogen or related polysaccharides. In the absence of staining, the result is considered negative (Moreno et al., 2021; Wang & Hong, 2022).

2.5 Obtaining Fibre from Corn Cobs

The stalks, collected at the Maluku market, were cut up, washed to remove impurities, and then dried in the sun for 24 hours. They were then crushed to obtain a lignocellulosic powder.

Alkaline Processing Step

A 50 g sample of powder was placed in a 500 mL Erlenmeyer flask and then mixed with 500 mL of NaOH (1 mol/L). The mixture was heated to 80 °C for 1 hour under stirring. After filtration, the residue was washed thoroughly with distilled water to remove traces of NaOH. The resulting fibres were dried in an oven at 50 °C for 19 h and then bleached. This process is consistent with recent practices for the chemical treatment of lignocellulosic biomasses to obtain reinforcing fibers (Dewan et al., 2024).

Whitening stage

To bleach the delignified fibres, 25 g of dry fibre was stirred in a mixture of 200 mL of distilled water, 1 mL of acetic acid and 3 g of $NaClO_2$ at 70°C for 2 h. After vacuum filtration, the fibres were washed with distilled water until a neutral pH was reached. They were then dried in an oven at 50 °C for 19 hours, sieved and stored for later use. This protocol is in line with modern methods for the recovery of agricultural waste for the production of nanocellulose and functional fibers (Alam et al., 2024).

2.6. Production of bioplastic films

Bioplastic films were developed by the method of solvent casting followed by evaporation, in accordance with the protocols described in the literature (Tan et al., 2022; Sharma et al., 2025). The experimental procedure is detailed below.

1. *Preparation of the initial mixture*

A mixture containing 3 g of glycogen powder, 2 mL of glycerol (plasticizer) and 3 mL of hydrochloric acid (HCl, 0.1 N) was dispersed in 20 mL of distilled water. The suspension was shaken at 180 rpm for 15 minutes at room temperature. The addition of a dilute acid facilitates partial glycogen hydrolysis and improves the solubilization of polysaccharides (Sheikh et al. 2025).

2. *Glycogen gelatinization*

The homogeneous mixture was then heated using a heating plate under constant stirring until 90 °C was reached, allowing glycogen gelatinization. This temperature is commonly used for the complete gelatinization of glycogen granules, leading to an increase in the viscosity of the medium (Di Caprio et al., 2024).

3. *Incorporation of cellulosic fibers*

Once the temperature of 90 °C was reached, the cellulosic fibre powder was added to the mixture in different glycogen /fibre mass ratios: 10:0, 9:1, 8:2, 7:3 and 6:4. These proportions correspond respectively to the following samples:

- FNR: unenhanced biofilm (10:0)
- FR1: Enhanced Biofilm 1 (9:1)
- FR2: Enhanced Biofilm 2 (8:2)
- FR3: Enhanced Biofilm 3 (7:3)
- FR4: Enhanced Biofilm 4 (6:4)

The addition of cellulosic fibers improves the mechanical properties and thermal stability of bioplastic films (Abed et al., 2024; Kumar et al., 2026).

4. *Gel formation*

Stirring and heating were maintained for 15 minutes until a viscous, sticky solution was obtained, characteristic of the formation of a thermoplastic gel. This step promotes the interaction between the glycogen matrix and cellulosic fibers (Sheikh et al., 2025).

5. *Neutralization and viscosity adjustment*

Three millilitres of sodium hydroxide (NaOH, 0.1 N) were then added to neutralize the acidity of the medium and reduce the viscosity of the suspension. The thermal agitation was prolonged for 5 minutes. NaOH neutralization is essential to stop acid hydrolysis and adjust pH, which influences film formation (Sheikh et al., 2025; Di Caprio et al., 2024).

6. *Casting and drying*

The hot suspension, having the consistency of a gel, was poured onto flat glass plates. These were placed in the oven at 70 °C for 1 hour, then drying continued at room temperature until a constant mass was obtained, indicating the complete removal of the solvent. The drying temperature directly influences the mechanical properties and transparency of the films; a temperature of 70 °C is commonly used to prevent thermal degradation while ensuring rapid drying (Nikhilesh & Jethva, 2023; Sharma et al., 2025).

2.7 Characterization of bioplastic films

The bioplastic films produced in this work were subjected to a series of characterization tests to evaluate their physicochemical and functional properties. Parameters studied include drying time, thickness, moisture content, water holding capacity and flame behaviour. These analyses are essential to determine the quality and performance of bioplastics, in line with recent practices in the characterization of bio-based polymeric materials (Tan et al., 2023).

2.7.1 Drying Time

The drying time of the prepared films was evaluated according to the method proposed by (Sheikh et al. (2025). Each formulated film was weighed before the drying process began, and then the weight evolution was monitored daily until a constant weight was achieved. The time required to reach this constant weight was recorded as the drying time. This method is consistent with recent protocols for monitoring the drying kinetics of biopolymers.

2.7.2 Thickness

The thickness of the films produced was measured using a Holex handheld micrometer, at different randomly selected points on each sample. The measurements were carried out in triplicates and the average value was calculated. Thickness is a critical parameter influencing the mechanical strength and permeability of bioplastics, as highlighted by recent work on polysaccharide-based films (Jabeen et al., 2022).

2.7.3 Moisture content

The water content (TH) was determined by evaluating the weight loss of the films during drying, according to ASTM D644. The initial weight of the films (mh) was measured and then the films were dried in the oven at 105 °C for 3 h. The final weight (dm) was then recorded. The water content was calculated based on the difference between mh and ms. This method is widely used in the recent literature to assess the stability of bioplastic films (Sheikh et al. 2025).

$$\boldsymbol{H\ (\%) = \frac{mh - ms}{mh} \times 100}$$

2.7.4 Water Holding Capacity (W.C.)

The water holding capacity was determined according to the method described by Tan et al. (2022). A known mass of dried film was immersed in a beaker of distilled water for 5 to 10 minutes and then weighed after immersion. The water holding capacity was calculated from the difference in mass between the dry

and wet sample. This parameter is essential for assessing the functionality of bioplastics in humid environments, and it is regularly reported in recent studies on biodegradable films (Jabeen et al., 2022).

$$C.R = me - ms$$

With

C.R: Water retention capacity.

me: Mass of the wet film

ms: Mass of the dry film

2.7.5 Combustion test

The combustion test was conducted according to ASTM D3801. The bioplastic films were exposed to the flame of a Bunsen burner. The observations focused on the smell released, the colour of the flame, the rate of combustion and the possible presence of sparks. These results were compared with data from the literature. This test verifies the safety and thermal resistance of bioplastics, in accordance with modern practices for characterizing bio-based materials (Tan et al., 2022).

2.7.6 Biodegradability

Biodegradation is defined as the decomposition of organic matter by the action of microorganisms such as bacteria, fungi, or algae. It is assessed by considering both the degree of decomposition of a substance and the time required to achieve this decomposition.

In this study, biodegradability was estimated by measuring the mass loss of biofilms as a function of time. The methodology was designed to align with the principles of **ISO 14855** and **ASTM D5338** – standard test methods that determine the aerobic biodegradation of plastic materials under controlled composting conditions. Although these standards typically require thermophilic temperatures and measurement of evolved carbon dioxide, the present study adapted a gravimetric approach (mass loss) for initial screening under mesophilic soil conditions.

To carry out the test, samples were taken from each biofilm, weighed (initial mass, Mi), and then buried in boxes containing 200 g of soil previously soaked with water. The samples were placed at a depth of 3 cm for 16 days. After 4 days (i.e., at the end of the incubation period), the samples were removed and weighed again to obtain the final mass (Mf). The mass loss was calculated using the following formula:

$$Mass\ loss\ (\%) = \frac{Mi - Mf}{Mi} \times 100$$

This gravimetric assessment of mass loss provides a complementary indication of biodegradability, consistent with recent methodologies for characterizing bio-based materials (Delamarche, 2021). Following the framework of ISO 14855 and ASTM D5338, higher mass loss over time would indicate greater aerobic biodegradability under the tested soil conditions.

3. Results and discussions

3.1. Species identified at the different sites of Maluku

Table I shows the different collection stations of our cyanobacteria. It appears that these stations are suitable environments for the proliferation of cyanobacteria according to the observation. Indeed, the conditions are well met (low water level, abundant light, abundance of substrates in the environment). The Nganda Musoko Pond had a higher cyanobacteria bloom than the Mutambwe stream due to its more favourable conditions for the growth of cyanobacterial biomass (see figure 2).

Table I. Cyanobacteria harvesting stations in Maluku

Harvesting stations	Watercourses	Water height	Contact Information Geographical
Maluku (Professor Mutambwe's concession)	The Mutambwe stream	≤12m	15° 32'45°E
Maluku (Nganda musoko)	Nganda musoko Pond	≤15m	S 15° 32'50°E

Figure 2: The Mutambwe stream (a) and Nganda musoko Pond (b)

3.2 Species Identified

We have listed 2 species of cyanobacteria as represented in table II.

Table II: Inventories of species collected at the Maluku site.

Sites	Reign	Order	Family	Genus	Species
Mutambwe stream	Bacteria	Schizotrichales	schizotrichaceae	Schizothrix	*Schizothrix lacustris*
Nganda musoko Pond	Bacteria	schizotrichales	schizotrichaceae	Schizothrix	*Schizothrix chromosiphon*

The images of cyanobacteria with the 10X10 objective (see figure 3) illustrate the microscopic presentations of each species.

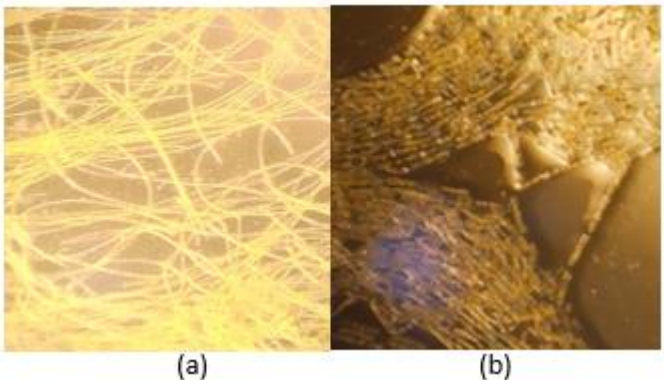

Figure 3: Microscopic species observed: (a) Schizothrix lacustris, (b) Schizothrix chromosiphon

The presence of Schizothrix lacustris (Nganda Musoko pond) and Schizothrix chromosiphon (Mutambwe stream) confirms the diversity of filamentous cyanobacteria sheathed in Maluku, in agreement with the work of Temraleeva (2018) who emphasizes that the distribution of Schizothrix is influenced by edaphic and water parameters. Komárek et al. (2006) showed that the ultrastructure of the filaments and the morphology of the sheaths make it possible to distinguish these two species, which our microscopic observations (figure 3) corroborate. Contrary to the work of Temraleeva (2018) in Russian arid soils where Schizothrix dominates in the Nostocales and Synechococcales communities, our tropical aquatic sites have a more limited diversity (2 species), possibly related to specific local environmental conditions. Komárek et al. (2006) insist on the importance of polyphasic approaches (morphology + genetics) for the identification of Schizothrix, an approach to be extended to our samples to confirm these taxa.

3.3 Characterization of Schizothrix lacustris

3.3.1 Lugol Test, Moisture and Ash Levels

Table III presents the results of the lugol test on the species and the values of the moisture and ash levels of our biomass as well as the standards that govern them.

Table III: Lugol test values, moisture content and ash content

Tests	Values	Standards
Lugol	Positive (+)	-
Humidity	69%	ISO 712 :2009
Ash content	8,5%	ISO-5984 2009

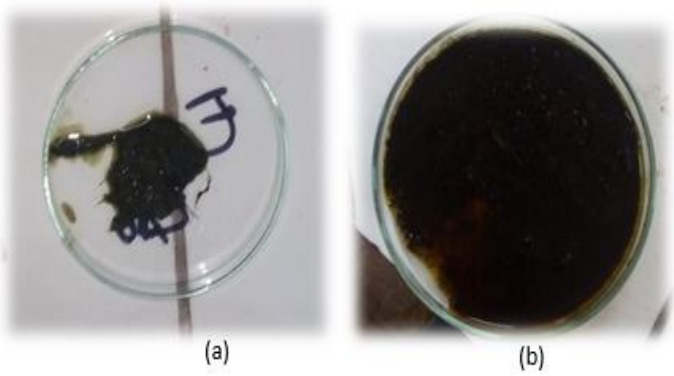

Figure 4: algae before contact with lugol (a) and cyanobacteria after contact with lugol (b)

The positive Lugol test confirms the presence of glycogen in Schizothrix lacustris, a result consistent with Mohamed et al. (2023) who use this staining to detect storage polysaccharides in toxic cyanobacteria of the genus Schizothrix. The humidity level of 69%, in accordance with ISO 712:2009, compares to the values reported by Temraleeva (2018) for cyanobacteria from Russian arid soils (60-75%), suggesting a similar ecological adaptation despite contrasting habitats. Komárek et al. (2006) point out that the ultrastructure of the ducts in Schizothrix influences water retention, which could explain our relatively high humidity level.

The ash content of 8.5% in this work reflects a moderate mineral load, lower than the 10-12% reported by Mohamed et al. (2023) for Schizothrix strains in a eutrophic environment, indicating a lower accumulation of carbonates or phosphates in our biomass. These inter-site differences underline the impact of environmental conditions (freshwater compared to arid soils and eutrophic environments) on the biochemical composition of cyanobacteria of the genus Schizothrix.

3.3.2 Physicochemical Parameters of the Growth Medium

The different physicochemical parameters of the water in the growth medium of the different sampling sites are distributed in table IV.

Table IV: Physicochemical Parameters of Sampling Site Water

Settings	The Mutambwe stream (n=3)	Nganda musoko Pond (n=3)	ANOVA (p)
Conductivity (µS)	6,00 ± 0,17	22,00 ± 0,17	< 0,001
Salinity (ppt)	0	0	
TDS (ppm)	9,00 ± 0,17	36,00± 0,17	< 0,001
pH	6,50 ± 0,17	6,60 ± 0,17	0,230 (NS)
Temperature	29,40 ± 0,17	34,30 ± 0,17	< 0,001

It is apparent from this table that:

Conductivity and TDS: Nganda Musoko Pond (22, 00 ± 0, 17 µS; 36, 00± 0, 17 ppm) has higher values than Mutambwe Creek (6, 00 ± 0,17µS; 9, 00 ± 0, 17 ppm), reflecting greater ion and nutrient availability. Recent studies confirm that high mineralization promotes the productivity of cyanobacteria in freshwater (Antoine, 2009).

pH: Both sites have a slightly acidic pH (6,50 ± 0,17 – 6,60 ± 0,17). Although optimal growth of cyanobacteria is around neutral, they tolerate moderate variation, which explains their presence in these environments (Gaysina, 2024).

Temperature: The pond reaches 34, 30 °C compared to 29, 40 °C for the stream. High temperature stimulates cyanobacterial metabolism, but above 35 °C, some species see their growth reduced (Filali et al., 2021).

Salinity: The zero salinity in the two sites confirms a strictly freshwater environment, favourable to freshwater species.

The Mutambwe stream appears oligotrophic, with a low ionic load, while the Nganda Musoko pond is more eutrophic, conducive to a higher cyanobacterial biomass but potentially exposed to the risk of eutrophication.

3.4 Glycogen Extraction

Table V. gives the glycogen yield

Biomass Type	Biomass mass (g)	Cyanobacteria glycogen mass (g)	Yield (%)
***Schizothrix lacustris* Cyanobacterium**	500	330,14	66,03 ± 0,28 (n= 3)

The glycogen extraction yield for Schizothrix lacustris (66.03%) is above the maximum range reported for tubers and roots (10–65%, Dorantes-Fuertes et al., 2024), demonstrating the competitiveness of this cyanobacterium compared to traditional agricultural sources. Compared to microalgae, this result remains below the maximum of 80% achievable according to Di Caprio et al. (2024), a gap that is probably explained by the lack of specific optimization of the extraction process. As Vidal & Venegas-Calerón (2019) point out in Synechocystis sp., culture conditions (including nitrogen deficiency) and cell lysis efficiency are key factors directly influencing glycogen yield. Thus, the result obtained in this study confirms the potential of Schizothrix lacustris as a sustainable alternative, while indicating that there is significant room for improvement. The adoption of advanced techniques (enzymatic extraction, mechanical pre-treatments or nutritional stress) could make it possible to achieve the highest standards of the bioeconomy.

3.5 Cellulosic Fiber Extraction

Table VI shows the yield in terms of percentage of cellulosic fibres obtained from 60g of maize cob powder.

Table VI: Yield of cellulosic fibres obtained from maize cobs

Starting masses of the cob powder	Masses after delignification	Masses after bleaching	Yield
60,01 g	44,63 ± 0,21g	28,90 ± 0,20 g	48,17 ± 0,33 %

ANOVA: F (1,4) = 8788; p < 0,001

The yield (48.16%) obtained is comparable to that obtained for rice straw (about 48%) but lower than that of cane bagasse (up to 55%) reported by Thongsomboon et al. (2023). According to Woiciechowski et al. (2020), alkaline pretreatments (delignification) effectively remove lignin but can also solubilize some of the non-cellulosic polysaccharides, explaining the observed mass loss (60 g → 44.64 g). Bleaching then reduced the mass to 28.90 g, a loss consistent with the removal of lignin and hemicellulose residues. Thus, the yield of 48.16% is satisfactory and competitive with regard to certain residues, but an optimization of the parameters (time, temperature, alkaline concentration) could make it possible to reach the 55% reported for cane bagasse.

3.6. Characteristics of Bioplastic Films

Bioplastic films of different formulations (FNR, FR1, FR2, FR3 and FR4) were prepared by casting-evaporation.

3.6.1 Physical Aspects of Films

Table VII presents the aspects of the different films formulated.

Table VII. Aspects of Formulated Bioplastic Films

Films	FNR	FR1	FR2	FR3	FR4
Color	Green	Greenish	Greenish	Greenish	Greenish
Observation	Flexible Gooey	Flexible Less gooey	Flexible Less gooey	Very light Less flexible Less gooey	Flexible Resistant Not gooey

The resulting films show an evolution of the physical properties: the control (FNR) is green, flexible but sticky, while the formulated films (FR1–FR3) gradually become less gooey and less flexible.

The gradual improvement in the flexibility from FR1 to FR4 corroborates the crucial importance of the effect of additives highlighted by Sheikh et al. (2025) to balance the flexibility and cohesion of biopolymer films, by mechanically optimizing their films (GMP-II: 0.42 MPa). Thus, FR4 appears to be the most efficient, suitable for applications such as biodegradable packaging.

3.6.2 Results of the characterization of the films obtained

The values of the drying time, thickness, water content, and water holding capacity of the 5 resulting formulations are presented in figure 5, while those of the combustion test are presented in table VIII.

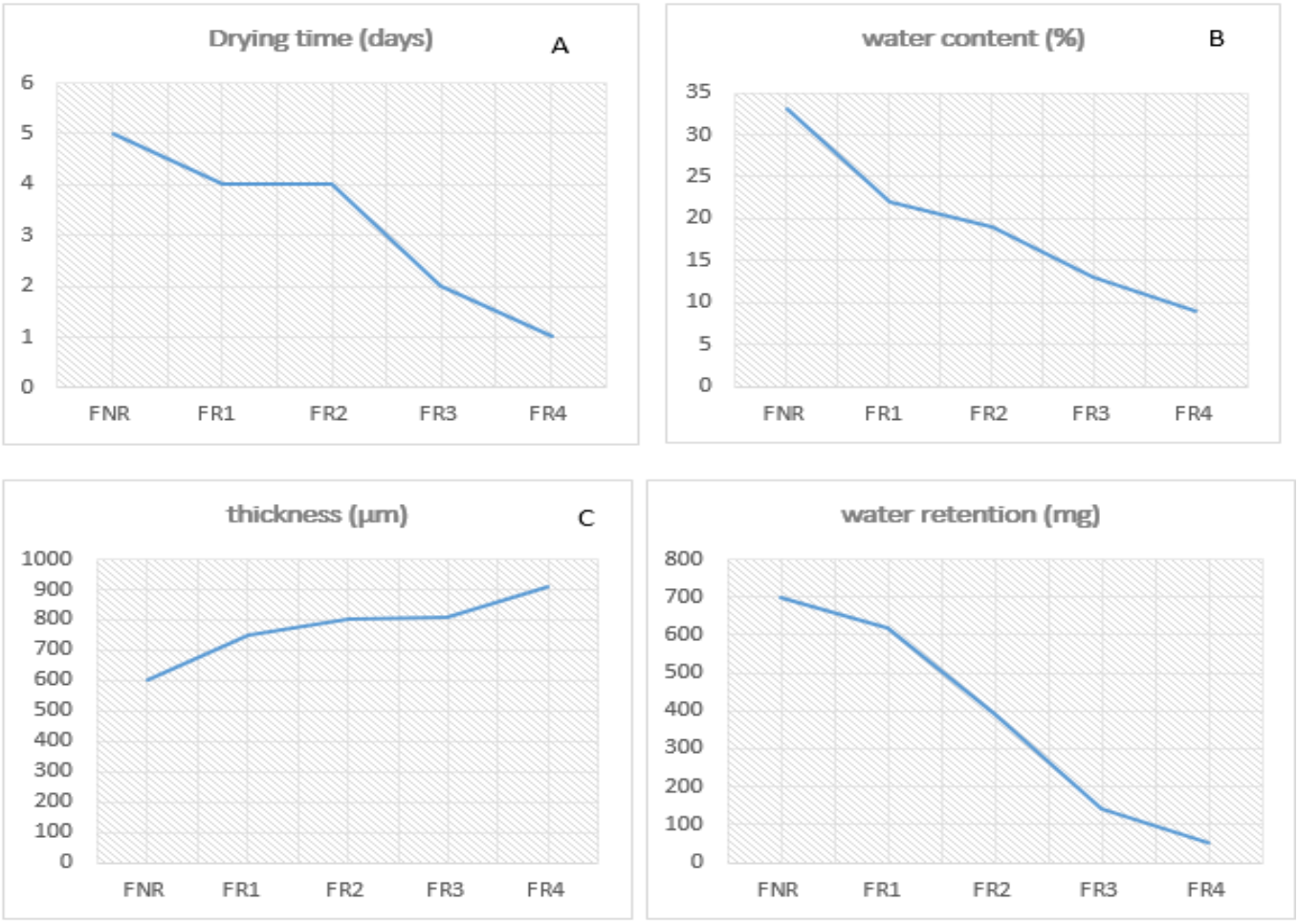

Figure 5: The values of drying time (A), thickness (C), water content (B) and water retention (D).

The results obtained in this study show that the addition of cellulosic fibers (FR3/FR4) reduces the drying time (5 → 1-2 days) and the water content (33 → 13-9%) compared to the pure glycogen film (FNR), reflecting better water stability. Sheikh et al. (2025) observed similar improvements on banana peel films with an optimized plasticizer/hydrolyzer ratio (1:2), highlighting the importance of proportions in reducing hygroscopy. The increase in thickness (600 → 910 µm) suggests a densification of the matrix, which, according to Tan et al. (2022) on starch-chitosan films, can limit flexibility while improving moisture resistance. The drastic decrease in water holding capacity (700 → 50 mg) reflects a reduction in porosity, comparable to the results of Narancic et al. (2020) who associate this property with a better durability of bioplastics in humid environments. Fiber-rich formulations (FR3/FR4) prioritize water stability and mechanical strength at the expense of absorption, a trade-off already documented by Sheikh et al. (2025) for sustainable packaging applications.

3.6.3 Combustion Test

Test	FNR	FR1	FR2	FR3	FR4
Ignition time	Short	Short	Medium	Long	Long
Flame propagation rate	Slow	Slow	Medium	Fast	Fast
Residue formation	Low	Low	Medium	Significant	Significant
Smoke production	Low	High	High	High	High

The study by Tan et al. (2022) reveals a structure-function correlation: the addition of chitosan enhances starch-chitosan cross-linking by hydrogen bonds, increasing the cohesion of the material. This explains why the FR3/FR4 tests (ignition time: Long, residue formation: Important) show better initial thermal resistance and slower degradation, as observed by Tan et al. (Stability up to 290 °C and 52.1% mass loss after 28 days). Regarding the speed of flame spread, once degradation has begun, the stiffer structure (less plasticized) promotes a lively spread, generating more carbonized residues.

Conversely, the "Low" residue formation tests (FNR, FR1) are likely to correspond to a higher glycerol content, which Tan et al. have shown to reduce cohesion and accelerate pyrolysis, producing less residue but more smoke (FR1). Finally, the FR2 ("Average" for flame velocity) test seems to represent the optimal compromise between plasticity and stability, close to the optimal conditions of Tan et al. (70 °C, 40% glycerol), offering a moderate combustion without excess residues or excessive smoke.

Figure 6: Burn test result of FR4 bioplastic films

3.6.4. Biodegradability

The figure below shows the results of the biodegradability of the biofilms obtained

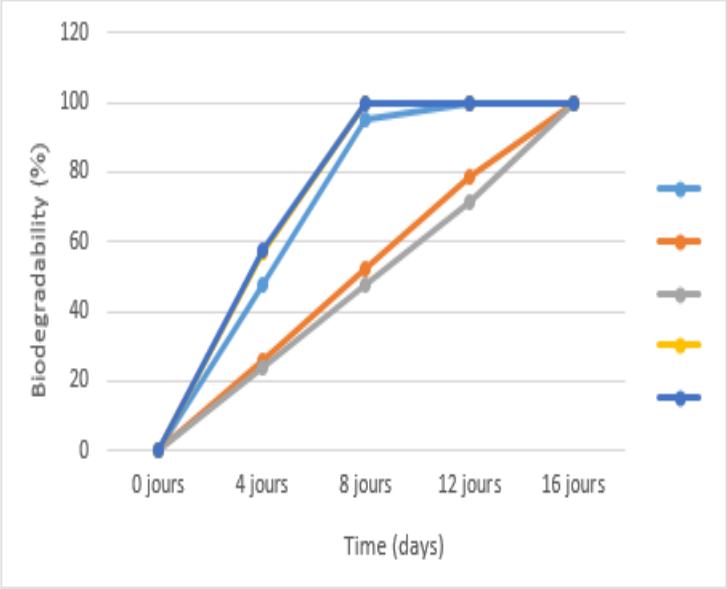

Figure 7: Evolution of mass loss as a function of time for the 5 formulations

The biodegradation kinetics (100% at 12-16 days depending on the formulation) corroborate Narancic et al. (2020): degradation depends on enzymatic accessibility, with pure glycogen (FNR, 83.4% at 7 days) degrading faster than composites. This effect is consistent with Sheikh et al. (2025) on banana peel films, where an optimal plasticizer/hydrolyzer ratio (1:2) resulted in 91% degradation at 60 days, highlighting the importance of proportions. The

nonlinear effect of cellulosic reinforcement is consistent with Tan et al. (2022) on starch-chitosan films: intermediate loads (FR1/FR2: 41-45% at 7 days) densify the network and slow down hydrolysis, while high rates (FR3/FR4: 100% from day 8) create porosity accelerating degradation. Sikora et al. (2020) show that the addition of fillers changes the crystallinity of bioplastics, affecting their biodegradability. According to Emadian et al. (2017), biodegradation in the natural environment depends on the polymer structure and microbial conditions, explaining our kinetic differences.

4. Conclusion

The aim of this study was to produce biofilms from cyanobacteria, a third-generation biomass, and to improve their properties by incorporating cellulosic fibres extracted from maize cobs. The biofilms were formulated with different proportions of fibers: 0% (FNR), 10% (FR1), 20% (FR2), 30% (FR3) and 40% (FR4).

The results obtained show that the gradual addition of fibers significantly improved several physicochemical properties of the films. The drying time decreased from 5 days (FNR) to 1 day (FR4), while the thickness increased from 0.60 mm to 0.91 mm. The water content was reduced from 33% (FNR) to 13% (FR4), and the water holding capacity was reduced from 0.70 g to 0.05 g. Regarding the combustion test, all the films showed a yellow-orange flame, with an increasing burning rate depending on the proportion of fibers. These results confirm the valorization of cyanobacteria (Schizothrix lacustris), containing 66,03 ± 0,28 % extractable glycogen, and corn cobs, capable of providing about 48,17 ± 0,33 % cellulosic fibers.

The integration of the fibers improved the quality of the biofilms, including the reduction of hydrophilic character and their stability. This research demonstrates the potential of third-generation biomass and agricultural waste in the production of sustainable bioplastics, paving the way for promising applications in the field of eco-friendly packaging.

Acknowledgments

The authors express their gratitude to the study participants, as well as to the anonymous reviewers.

Funding

This research was financed from its own funds.

Conflict of interest

The authors state that there is no conflict of interest regarding this study.

Ethical considerations

The study was conducted in accordance with the ethical principles of research.

Author contributions

M.K.A: Study design, fiber extraction and manuscript writing.

B.M.E: Study design and fiber extraction.

M.K.I: Study design and fiber extraction

B.M.N: Data curation, preparation of figures and tables, and assistance in drafting the results section.

N.N.C: Environmental risk assessment, interpretation of ecological impacts of used oil disposal, and contribution to sustainability perspectives in the manuscript.

K.K.T: Scientific supervision and validation of results.

K.M.H: Physico-chemical analyses and characterization of films.

L.O.P: Sample collection and biomass preparation.

T.K.M: Statistical processing and interpretation of the data.

N.K.J: General coordination, correspondence and final revision of the manuscript.

Orcid of authors

Muabu K.A: https://orcid.org/0009-0005-2343-2310

Mulumba K.I: https://orcid.org/0009-0003-3034 4181

Bolangongo M.N : https://orcid.org/0009-0005-0215-3312

Ngoyi N.C: https://orcid.org/0009-0003-2282-5820

Kashishi K.T: https://orcid.org/0009-0000-6597-7371

Taba K.M: https://orcid.org/0009-0002-2784-9333

Ntumba K.J: https://orcid.org/0009-0003-1914-3741

References

Abed, E. H., Abdulhay, H. S., & Abbas, A. H. (2024). Assessment of solubility, moisture content, water absorption and thickness of bioplastic synthesized from Iraqi Amber rice husks. *African Journal of*

Biomedical Research, 27(3s), 1334–1341. https://doi.org/10.4314/ajbr.v27i3s.15

Alam, M. A., Gafur, M. A., & Al-Amin, M. (2024). Sustainable extraction and bleaching of lignocellulosic fibers from maize cob waste: Towards eco-friendly nanocellulose production. *Academia Preprint*. https://www.academia.edu/Isolation_and_characterization_of_CNC_from_waste_maize_cob

Antoine, M. (2009). *Analyse et gestion du risque cyanobactéries/cyanotoxines dans les eaux de baignade et les eaux destinées à la consommation humaine du département de la Haute-Vienne* [Mémoire de l'École des hautes études en santé publique]. https://documentation.ehesp.fr/doc_num.php?explnum_id=6505

ASTM International. (2018). *Standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions, incorporating thermophilic temperatures* (ASTM D5338-18). ASTM International. https://www.astm.org/D5338-18.html

Babaremu, K., et al. (2022). Plastic waste management and climate change impacts. *Journal of Environmental Studies*, 45–60.

Delamarche, E. (2021). Développement d'une méthodologie d'évaluation de la dégradabilité, dédiée à l'éco-conception. Application à des formulations à base de polyesters biosourcés et biodégradables (Thèse de doctorat). Université de Lyon. https://theses.hal.science/tel-03405892v1

De Porcellinis, A., Frigaard, N.-U., & Sakuragi, Y. (2017). Determination of the glycogen content in cyanobacteria. *Journal of Visualized Experiments*, (125), e56068. https://doi.org/10.3791/56068

Dewan, S., Rahman, M. M., Hossain, M. I., Ghos, B. C., Rabby, M. M. R., Gafur, M. A., Al-Amin, M., & Alam, M. A. (2024). Isolation and characterization of cellulose nanocrystals from waste maize cob for multifunctional bio-nanocomposites. *South African Journal of Chemical Engineering*, 48, 1026–9185. https://doi.org/10.1016/j.sajce.2024.12.007

Di Caprio, F., Pedram, N., Brugnoli, B., Francolini, I., Altimari, P., & Pagnanelli, F. (2024). Exploring different processes for starch extraction from microalgae and synthesis of starch-chitosan plastic films. *Bioresource Technology*, 413, 131516. https://doi.org/10.1016/j.biortech.2024.131516

Dorantes-Fuertes, M. G., López-Méndez, M. C., Martínez-Castellanos, G., Meléndez-Armenta, R. Á., & Jiménez-Martínez, H. E. (2024). Starch extraction methods in tubers and roots: A systematic review. *Agronomy*, 14(4), 865. https://doi.org/10.3390/agronomy14040865

Emadian, S. M., Onay, T. T., & Demirel, B. (2017). Biodegradation of bioplastics in natural environments. *Waste Management*, *59*, 526–536. https://doi.org/10.1016/j.wasman.2016.10.006

Filali, R., Tian, H., Micheils, E., & Taidi, B. (2021). Evaluation of the growth performance of microalgae based on fine pH changes. *Austin Journal of Biotechnology & Bioengineering*, 8(1). https://hal.science/hal-04459112

Gaysina, L. A. (2024). Influence of pH on the morphology and cell volume of microscopic algae. *Plants*, 13(3), 357. https://doi.org/10.3390/plants13030357

Guiry, M. D., & Guiry, G. M. (2023). AlgaeBase: An online resource for algal taxonomy. National University of Ireland, Galway. https://www.algaebase.org

International Organization for Standardization. (2019). *Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions — Method by analysis of evolved carbon dioxide* (ISO 14855:2019). https://www.iso.org/standard/68526.html

Jabeen, N., Majid, I., & Nayik, G. A. (2022). Bioplastics and food packaging: A review. *International Journal of Food Science & Technology*, 57(1), 13–22. https://doi.org/10.1111/ijfs.15262

Kang, Y. O., Cho, Y., Park, W., Kim, S., & Kang, H. Y. (2023). Environmental and economic performances of municipal solid waste management strategies based on LCA method: A case study of Kinshasa. *Heliyon*, 9(4), e15284. https://doi.org/10.1016/j.heliyon.2023.e15284

Komárek, J., Taton, A., Šulek, J., Wilmotte, A., Kaštovská, K., & Elster, J. (2006). Ultrastructure and taxonomic position of two species of the cyanobacterial genus *Schizothrix*. *Cryptogamie, Algologie*, *27*(1), 53–62.

Kumar, S. D., Mehta, P., & Rao, V. (2026). A comprehensive review of renewable bioplastics with a focus on algae-derived alternatives.

Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-025-07027-0

Mavula Damusa, L., Muabu Kayeye, A., Kamwiziku Mihala, J., Kashishi Kazadi, T., Kalulu Muzele, T., & Ntumba Kankolongo, J. (2024). Essai de production de l'acide polylactique (PLA) à partir de la mélasse de canne à sucre en vue d'élaborer les emballages bioplastiques. *Revue Congolaise des Sciences et Technologies*, *3*(3). DOI: https://doi.org/10.59228/rcst.024.v3.i3.96

Mohamed, V.B.H., Pasumalaiarasu, S., Parangusadoss, K. (2023). Isolation of Toxins Producing Cyanobacteria from Aquatic Sample with Schizothrix. In: Thajuddin, N., Sankara narayanan, A., Dhanasekaran, D. (eds) Protocols for Cyanobacteria Sampling and Detection of Cyanotoxin. Springer, Singapore. https://doi.org/10.1007/978-981-99-4514-6_14

Moreno Osorio, J. H. J., Pollio, A., Frunzo, L., Lens, P. N. L., & Esposito, G. (2021). A review of microalgal biofilm technologies: Definition, applications, settings and analysis. *Frontiers in Chemical Engineering*, 3, 737710. https://doi.org/10.3389/fceng.2021.737710

Narancic, T., Cerrone, F., Beagan, N., & O'Connor, K. E. (2020). Recent advances in bioplastics: Application and biodegradation. Polymers, 12(4), 920. https://doi.org/10.3390/polym12040920

Nikhilesh, A., & Jethva, K. R. (2023). Optimization of drying temperature for enhanced physical and mechanical properties of bioplastic films. *Journal of Polymer Research*, 30(4), 112–120. https://doi.org/10.1007/s10965-023-03456-9

OECD. (2023). Global Plastics Outlook: Drivers, Impacts and Options. OECD Publishing. https://doi.org/10.1787/aa1edf33-en

Piao, Z., Li, H., & Chen, Y. (2024). Environmental impacts of biodegradable microplastics. *Nature Chemical Engineering*. https://doi.org/10.1038/s44286-024-00127-0

Sarker, N. K., & Kaparaju, P. (2025). Advances in algae-based bioplastics: From strain engineering to sustainability. *Fermentation*, 11(10), 574. https://doi.org/10.3390/fermentation11100574

Sharma, S., Gupta, R., & Patel, A. (2025). Bioplastics as next-generation eco-friendly materials. *Clean Technologies and Environmental Policy*, 27, 5009–5027. https://doi.org/10.1007/s10098-025-03214-9

Sheikh, S., Amin, F., & Iqbal, Y. (2025). Sustainable synthesis and characterization of bioplastic films from whole banana peel: A comparative study on plasticizer–hydrolyzer ratios. *Chemical Papers*, 79, 6999–7009. https://doi.org/10.1007/s11696-025-04241-y

Sikora, J., Majewski, Ł., & Puszka, A. (2020). Modern biodegradable plastics—processing and properties: Part I. *Materials*, *13*(8), 1986. https://doi.org/10.3390/ma13081986

Tan, S. X., Ong, H. C., Andriyana, A., Lim, S., Pang, Y. L., Kusumo, F., & Ngoh, G. C. (2022). Characterization and parametric study on mechanical properties enhancement in biodegradable chitosan-reinforced starch-based bioplastic film. *Polymers*. https://doi.org/10.3390/polym14020278

Temraleeva, A. D. (2018). Cyanobacterial diversity in the soils of Russian dry steppes and semideserts. *Microbiology*, *87*(2), 249–260. https://doi.org/10.1134/S0026261718020169

Thongsomboon, W., Baimark, Y., & Srihaman, P. (2023). Valorization of cellulose-based materials from agricultural waste: Comparison between sugarcane bagasse and rice straw. *Polymers*, *15*(15), 3190. https://doi.org/10.3390/polym15153190

Vidal, R., & Venegas-Calerón, M. (2019). Simple, fast and accurate method for the determination of glycogen in the model unicellular cyanobacterium Synechocystis sp. PCC 6803. *Journal of Microbiological Methods*, *165*, 105686. https://doi.org/10.1016/j.mimet.2019.105686

Wang, X., & Hong, Y. (2022). Microalgae biofilm and bacteria symbiosis in nutrient removal and carbon fixation from wastewater: A review. *Current Pollution Reports*, 8, 128–146. https://doi.org/10.1007/s40726-022-00226-4

Woiciechowski, A. L., Dalmas Neto, C. J., Vandenberghe, L. P. S., Carvalho Neto, D. P. de, Sydney, A. C. N., Letti, L. A. J., Karp, S. G., Zevallos Torres, L. A., & Soccol, C. R. (2020). Lignocellulosic biomass: Acid and alkaline pretreatments and their effects on

biomass recalcitrance—Conventional processing and recent advances. *Bioresource Technology*, *316*, 122848. https://doi.org/10.1016/j.biortech.2020.122848

Zhang, Y., Li, J., Chen, Y., & Liu, J. (2023). Advances in microalgae harvesting and pretreatment for biofuel production. *Renewable and Sustainable Energy Reviews*, 174, 113123. https://doi.org/10.1016/j.rser.2023.113123