# THE ENERGY POTENTIAL OF DIFFERENT BIOMASS FRACTIONS OF *TYPHA DOMINGENSIS* GROWN IN GREEN FLOATING FILTERS

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ABSTRACT: Cattails (*Typha* spp.) have been used for Green Floating Filters (GFF) on the grounds that they have a great capacity to bioremediate eutrophic waters and produce biomass, which could be used as a biofuel feedstock. Cattail shoots are rich in fibres, representing a potential source for biobased materials, solid biomass, or cellulosic bioethanol. However, rhizomes could be the most valuable fraction for bioethanol because at the end of the growth cycle they are rich in starch. This paper aims to determine the energy potential of different plant fractions of *T. domingensis* Pers. grown in a GFF system, and their properties as solid biofuel; the content in non-structural carbohydrates of the submerged biomass is also studied. Results of this work show that all plant fractions of GFF cattail biomass (leaves and shoots, roots, stumps, and rhizomes) have a high energy content. The quality of GFF cattail biomass, as determined by proximate analysis and starch content, differs according to the biomass fraction, in line with literature data. Therefore, a separate (or selective) harvest of the different biomass fractions is recommended according to the subsequent use of each fraction, either as solid or liquid biofuel.
Keywords: bioethanol, biomass, calorific value, perennial energy crops

## 1 INTRODUCTION

*Typha domingensis* Pers. (commonly known as cattail) is an aquatic perennial herb with annual growth cycle, widely distributed in wetlands throughout the world [1]. It has been reported for the aquatic flora of Spain, where it thrives in nutrient-rich or altered aquatic habitats of the Iberian Peninsula and the Balearic Islands [2]. Cattail has been used in Green Floating Filters (GFF) systems due to its great capacity to remove nutrients -mainly nitrogen and phosphorus- from eutrophic waters [3–7]. GFFs are innovative systems for wastewater treatment of small agglomerations [8,9]. In essence, GFFs can be regarded as a type of hydroponic crop because plants are grown in the absence of soil to enhance wastewater treatment [10]. Some experiments demonstrate that the capability of cattails to produce a large quantity of biomass is closely related to the nutrient availability in the water body [11–13]; moreover, cattail biomass could provide an income by generating renewable energy [6,14] and bioproducts [15].

Additionally, as compared to traditional energy crops, the main advantage of growing cattail in GFFs for wastewater treatment, including the valorization of the produced biomass, is that this cropping system would not necessarily imply Land Use Change (LUC) or require fertilizers. Several studies show that cattail shoots are rich in fibres at the end of the growth cycle and represent a potential biomass source for cellulosic bioethanol [16–18]. However, rhizomes are the most valuable plant fraction for bioethanol because they are rich in starch [19]; their starch content has been reported up to 70% of the dry mass [20].

This work aimed to determine the energy potential of different plant fractions of *T. domingensis* grown in a GFF system during a two-year experiment, as well as to study the quality of its whole biomass as solid biofuel and the carbohydrates content of the submerged biomass. The hypothesis underlying this work was that a separate (or selective) harvest of the different biomass fractions according to the subsequent use of each fraction, either as solid or liquid biofuel, would be an interesting alternative for the valorization of cattails biomass. This research is in line with SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy).

## 2 MATERIALS AND METHODS

### 2.1 Plant material

Seeds of *T. domingensis* came from the seedbank of the Agro-Energy Group (GA-UPM, 3º44'W, 40º26'N). The seeds were germinated and let grow in planting trays (335 x 510 mm, 96 cells) filled with a substrate made of 50% sand and 50% peat and maintained in water flooded conditions from February to June 2019. On day 115 after sowing, 240 healthy plants of similar size were randomly taken and established in an outdoor hydroponic system sited in the experimental fields of GA-UPM, simulating a GFF system (Fig. 1).

The GFF system was set up in a 4.5 $m^3$ pool (6 $m^2$ surface area, 0.75 m height) filled with a nutrient solution of 0.25 g $l^{-1}$ of Hakaphos® azul 20-5-5, a water soluble NPK(S) fertilizer with micronutrients; as floating trays, eight perforated sheets of expanded polystyrene (EPS) were used. The dimensions of each EPS sheet were 120 cm in length, 40 cm in width and 5 cm in height. Sheets had 59 perforations (holes) to hold plant balls and to allow roots to grow freely submerged in the nutrient solution, while shoots could emerge above the surface of EPS sheets [21].

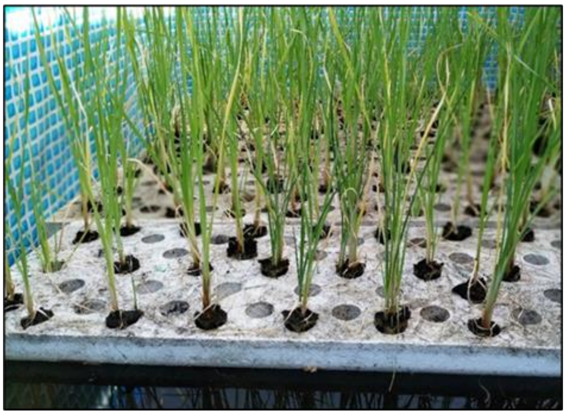

**Figure 1:** Cattail seedlings at the start of the GFF experiment.

Planting was performed in June 2019 using 30 seedlings per sheet. Daily air temperature (Fig. 2) and water pH were monitored during the GFF experiment by means of a HOBO U12 temperature data logger and a HQ40D multi-parameter meter, respectively. The range of pH was near neutral (5 to 6) while the range of $N\text{-}NH_4$ and $N\text{-}NO_3$ concentrations in the nutrient solutions was within the tolerance levels reported for *Typha* [22].

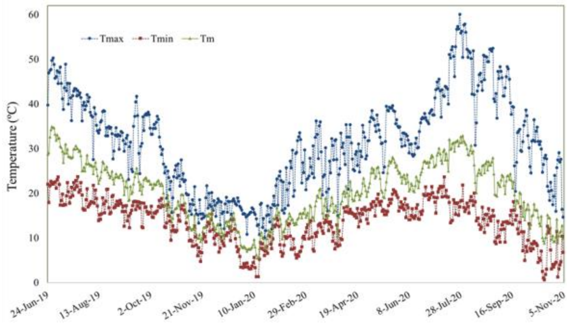


**Figure 2:** Maximum (Tmax), mean (Tmean) and minimum (Tmin) daily temperatures recorded during the GFF experiment.

2.2 Biomass production

After 21 months from the germination date of the cattail seeds, when the growth cycle was over (November 2020), the whole biomass was harvested. The number of EPS sheets evaluated for biomass production was eight, where each EPS sheet (EPSS) represented one sample.

All plants grown on a sheet were taken as a whole. Plants were fractionated into leaves/shoots, roots, stumps, and rhizomes, to be separately weighed and the whole biomass was washed with water; then, they were left to dry inside a greenhouse for 15 days. Afterwards, when the biomass was at equilibrium moisture, each plant fraction was sampled, weighed, and dried in an oven with forced air circulation at 65ºC for 72 hours in order to determine the dry matter content (%DM) of each plant fraction.

GFF's biomass production, broken down by plant fraction, was determined from the mass of EPSS plant fraction and the dry matter content of the biomass samples (%DM). The yield in dry biomass was referred to EPSS area (kg dry matter per EPSS square meter).

2.3 Biomass characterization

The dry biomass (equilibrium moisture) of each plant fraction was ground in a blade mill (RETSCH SM-100). Then, a 50 g sample was taken to be finely milled in an IKA A10 analytical mill. Afterwards, all samples were placed in sealed glass bottles until analysis.

The energy potential of the different biomass fractions was determined in terms of moisture-free Higher Heating Value ($HHV_0$) by means of a Leco AC-350 calorimeter (UNE-EN ISO 18125 norm). Biomass properties were assessed by proximate analysis, which includes the determination of the contents in moisture, ash (% on dry basis; UNE-CEN/TS 14775 EX norm), volatile matter (% on dry basis; UNE-EN ISO 18123 norm) and fixed carbon (FC, % on dry basis); FC was calculated as the difference between 100 and the sum of volatile matter and ash [21] The number of replicates per plant fraction was twelve.

The contents in free reducing sugars (FRS, water-soluble carbohydrates), total reducing sugars (TRS, hydrolyzed water extract) and starch (St, hydrolysis of the residue from water extraction) of the submerged biomass (rhizomes and roots) were determined according to the Nelson-Somogyi method [21].

Results were expressed in percentage (dry mass basis). In order to assess the potential application of the submerged biomass to ethanol production, the content in non-structural carbohydrates (TNC) of roots and rhizomes was calculated as the sum of starch and TRS.

## 3 RESULTS AND DISCUSSION

3.1 Biomass production

Results in Table I show the mean yield of cattails grown outdoor as GFFs, at harvest. Cattails were at the stage of senescence in November (harvest time); at that time shoots were dry whereas roots and rhizomes remained alive (dormant period of the annual growth cycle). At harvest, the rank order was leaves > stump > rhizomes > roots, representing 45.8%, 35.2%, 11.1%, and 7.9% of the total biomass, respectively.

**Table I:** Mean biomass yield of cattails grown outdoors as GFFs

| | Mean (t DM $ha^{-1}$) | % biomass fraction |
|---|---|---|
| Aerial biomass | 23.8 | 45.8 |
| Roots | 4.1 | 7.9 |
| Rhizomes | 5.8 | 11.1 |
| Stumps | 18.3 | 35.2 |
| Total yield | 52.0 | 100.0 |

The yield obtained in this study was equivalent to 52.0 t DM $ha^{-1}$ in nutrient-depleted conditions (average 20 mg $l^{-1}$ N); it was not possible to increase the nutrients level because the time in which the fertilization should have been carried out (March – June 2020) coincided with COVID-19 mobility restrictions.

The total biomass production in this study was much lower than in previous studies conducted in the same location. Thus, the mean yield reported by Martin and Fernandez attained 130 t DM $ha^{-1}$ $year^{-1}$ of total biomass for *T. latifolia* rooted in substrate receiving a secondary effluent from a sewage purification plant [23], and Curt et al. [24] reported 80 t DM $ha^{-1}$ for *T. domingensis* in conditions of high COD.

According to the literature review performed, cattail growth is closely related to nutrients availability. Cattails present higher biomass yield in eutrophic water conditions; however, they can be also grown in oligotrophic conditions, which seem to promote the allocation of biomass to roots [25].

3.2 Biomass properties

In Table II, the mean results of Higher Heating Value (moisture-free, $HHV_0$) of different plant fractions and the respective ANOVA are shown. Highly significant differences were found between plant fractions ($p<0.001$).

**Table II:** Mean values of Higher Heating Value ($HHV_0$, MJ $kg^{-1}$) of cattail plant fractions (aerial biomass, stumps, roots and rhizomes).

| Biomass fraction | $HHV_0$ (MJ $kg^{-1}$) |
|---|---|
| Aerial biomass | 18.83[b] |
| Stumps | 18.41[a] |
| Roots | 19.21[c] |
| Rhizomes | 18.37[a] |
| SEM | 0.07 |
| df | 31 |

The different letters after the values of the $HHV_0$ column represent statistically significant differences according to LSD test ($p < 0.05$).

HHV represents the amount of energy to be evolved by a biomass [26]. In our study, mean $HHV_0$ of *T domingensis* biomass was 18.7 MJ $kg^{-1}$, a value comparable to $HHV_0$ of some woody plant species such as *Acacia* spp. (18.9 MJ $kg^{-1}$), even to wood pellets (16.9-20.3 MJ $kg^{-1}$) according to Avellán & Gremillion [27].

In comparison with other species of *Typha*, the aerial biomass of *T domingensis* presented higher $HHV_0$ than *Typha x glauca* (16.0 MJ $kg^{-1}$) [28], *T. angustifolia* (17.2 MJ $kg^{-1}$) [29] and *T latifolia* (18.3 MJ $kg^{-1}$) [30], as well as higher values than for other potential energy plant species (see Table III). Therefore, according to the results of this parameter, *T. domingensis* biomass could have a high potential for thermal applications.

**Table III:** Comparison of the energetic value of aerial biomass (Higher Heating Value moisture-free, $HHV_0$) between *Typha* species and potential energy plant species.

| Species | $HHV_0$ (MJ $kg^{-1}$) |
|---|---|
| *Typha x glauca* [28] | 16.0 |
| *T. angustifolia* [29] | 17.2 |
| *T. latifolia* [30] | 18.3 |
| *T. domingensis* [21] | 17.6 |
| *Phragmites australis* (Cav.) Trin. ex Steud. [28] | 17.2 |
| *Phalaris arundinacea L.* [31] | 17.4 |
| *Miscanthus giganteus* J.M. Greef [26] | 17.8 |
| *Arundo donax* L. [30] | 18.1 - 18.7 |
| *Lythrum salicaria* L. [30] | 16.6 - 18.6 |
| *Helianthus annuus* L. (hulls) [14] | 19.7 |
| *Sorghum bicolor* L. Moench [26] | 20-25 |

Biomass production and $HHV_0$ results in this study showed that the submerged biomass (stumps, roots, and rhizomes) presented higher energy production (520.8 GJ $ha^{-1}$) than the aerial biomass (449.1 GJ $ha^{-1}$) since energy production rate is mainly determined by the biomass production rate [32].

Although the value of $HHV_0$ is an important indicator of the amount of energy contained in the biomass, it is necessary to assess the quality of the biomass by a number of physical and chemical properties in order to determine the potential of a particular biomass as biofuel [27].

Among the various methods commonly used, the proximate analysis was the one chosen for this study.

Results showed significant differences between plant fractions (Fig. 3). On average, GFFs whole biomass presented 4.5% ash, 74.9% volatile matter (VM) and 20.6% fixed carbon (FC). Regarding plant fractions, the aerial biomass presented the highest content in ashes (6.3%) while the stumps contained slightly more VM (75.6%) than the other fractions, and the rhizomes, slightly more FC (21.9%).

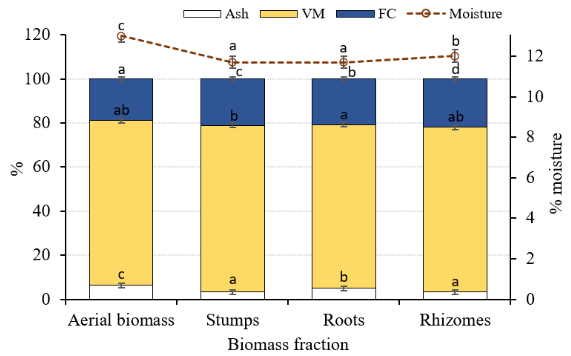


**Figure 3:** Proximate analysis of different plant fractions of cattails grown as GFFs. VM, volatile matter; FC, fixed carbon. The different letters after the values of the same column represent statistically significant differences according to LSD test ($p < 0.05$).

Table IV shows literature values of the proximate analysis of different plant species. VM embodies components of the biomass which can be readily burnt, such as hydrocarbons and organic acids, and it is higher in herbaceous biomass than in wood; in principle, high VM content suggests that adequate pathways for biomass valorization could be biomethanation or pyrolysis [33].

In our study, cattail plant fractions contained 74.9% VM on average, a value higher than for other aquatic biomass such as *Lemna minor* (L.) Griff and the algae *Plocamium telfairiae Harvey* ex Kütz, and for other types of biomasses such as rice straw and wood.

**Table IV.** Proximate analysis of some types of biomasses. Values in percentage.

| Species name | Ash content | VM | FC | Reference |
|---|---|---|---|---|
| *T. domingensis*[a] | 6.3 | 74.8 | 18.9 | This study |
| *T. domingensis* [a] | 9.9 | 71.9 | 18.3 | [21] |
| *T. latifolia* [a] | 10.0 | 71.9 | 18.1 | [6] |
| *T. angustifolia*[b] | 3.8 | 80.0 | 2.2 | [34] |
| *T. angustifolia* [a] | 10.9 | 72.0 | 17.1 | [29] |
| *L. minor*[b] | 18.7 | 59.0 | 18.8 | [33] |
| *Plocamium telfairiae*[b] | 33.2 | 30.6 | 24.3 | [35] |
| *Eucalyptus grandis*[a] | 0.4 | 78.2 | 21.3 | [34] |
| Wood stem[b] | 0.4 | 68.9 | 10.7 | [34] |

[a]Values on dry mass basis
[b]Moisture content reported by the referred authors for *T. angustifolia*, *L. minor*, *Plocamium telfairiae* and wood stem was: 13.9%, 3.5%, 11.7% and 8.8%, respectively.

Within the proximate analysis parameters, Ash and FC are also other very useful parameters to know the quality of a biofuel. The lower the ash content, the better the solid biofuel is. Thus, wood stem is low in ash, usually less than 1%. On the contrary, the ash content of different *Typha* species is high, often presenting values of more than 8% (Table IV).

According to Ciria et al. [6], the high ash content (10%) and ash composition of *Typha* could cause agglomeration and sintering problems in combustion processes. In our study, the mean value of ash was 6.3% for the aerial biomass of *T. domingensis* in GFFs.

However, in another study of *T. domingensis* grown in GFFs [21], a mean of 9.9% ash was reported. This high value was related to the presence of inorganic contaminants deposited on plant leaves [21]. In the present study, and to prevent this type of contamination, the whole biomass was washed with water before undertaking the proximate analysis. Washing seems to be a method to decrease the ash content. Although the mean value found in this work is not as high as that of rice straw (18.7%) [36] or the algae *Plocamium telfairiae* [35], it is still far from specifications for solid biofuels according to UNE-EN ISO 17225-1:2022 norm. Nevertheless, the biomass of *T. domingensis* could be used as a low-quality solid biofuel and combined with other higher-quality biofuels [14].

Another option for energy valorization of cattail biomass is the production of cellulosic ethanol (liquid biofuel), although a low ash content suggests the low probability of hydrolytic retarding of saccharification process during bioethanol fermentation according to Bin and Hongzhang [37]. Concerning the ash content, there were differences between plant organs in our study; thus, mean ash content in rhizomes and stumps was 3.3%, whereas in the aerial biomass and roots was 5.6%.

The FC value reflects the energy used by the biomass to char, where a high FC content indicates better quality of the biofuel [31], while a low FC suggests suitability for enzymatic biodegradation and anaerobic digestion processes [33]. In our study, the mean FC content was 18.9%, which is lower than the value reported for *Eucalyptus* (21.3%), but close to other values reported for *Typha* spp. (Table IV). The range of values reported for *Typha* spp. (Table IV) was from 17 to 19%, except for the value reported by Singh, Mahanta and Bora [34] (2.2% FC, biomass with 13.9% moisture content).

The moisture content is another important parameter, affecting the actual calorific energy of the biomass. According to Braga et al. [38], biomass containing less than 10% moisture is considered feasible for both combustion and different types of pyrolysis [26]. If the moisture content is higher, the energy yield decreases due to the fact that the moisture content of the biomass, at the time of combustion, results in a decrease of the amount of heat released, since part of the energy released in the combustion of biomass is used to convert water into steam [27]; in these cases, it is necessary a drying step before use. *Typha* spp. generally have a moisture content in the range of 7-30% after air-drying, but final moisture content varies depending on local conditions and time of harvest.

In the present study, moisture content of cattail plant fractions ranged from 10 and 14% (air-dry biomass). The aerial biomass and rhizomes presented significant higher values than roots and stumps (Fig. 3).

The content in non-structural carbohydrates (TNC) of rhizomes harvested in November reached a mean value of 30%. Out of the three categories of carbohydrates studied, the highest content was for the starch (Fig. 4), consistent with the fact that starch is the major reserve carbohydrate in *Typha* rhizomes. Thus, the TNC content in the rhizomes was higher than in the roots (Fig. 4); approximately 2.4, 9.5 and 1.6 times higher FRS, TRS and St, respectively, than in the roots. These results are in line with previous studies of GFFs *T. domingensis* [21].

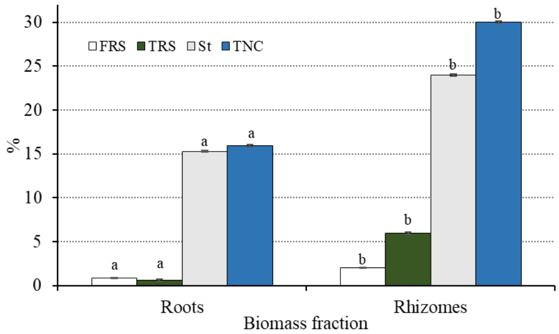


**Figure 4.** Mean percentages of free reducing sugars (FRS), total reducing sugars (TRS) and starch (St) according to the type of submerged biomass fraction. The different letters after the values of the same column represent statistically significant differences according to LSD test ($p < 0.05$).

An important factor for TNC content is the time in which the biomass is harvested because of the occurrence of seasonal changes in the allocation of carbohydrates to *Typha* organs [39–42]. Thus, in the aerial plant part, the starch is produced in the cells behind the marginal meristems of the leaves and in the parenchyma cells of shoots; in the roots, within mature stellar parenchyma and cortical cells; and in rhizomes, within the parenchymal cells of the central core of the rhizome [39]. Although cattail roots also store starch, most starch is concentrated on rhizomes, either produced directly or translocated from other plant organs [39].

According to Martin [41], part of the photoassimilates produced in the leaves of *T. latifolia* starts to translocate to the rhizomes at the end of summer, resulting in a strong and progressive accumulation of sugars and starch, whose maximum content remains steady approximately from November to February. Kausch, Seago and Marsh [39] showed that the parenchymal cells of the central core of the rhizome were filled with large, globose grains of starch in late autumn and mid-winter, but from late winter to spring, a significant reduction of the starch content in these tissues happened. Such reduction coincided with increasing bud growth and starch mobilization to shoot development [39]. Therefore, the harvest date of rhizomes is key for recollecting as much starch as possible [21]. The age of the rhizomes is also important since the youngest parts of rhizomes contain a higher proportion of starch compared to the older parts, as reported for *T. angustifolia* [43]. The literature review performed prior to the start of our field experiment advised to harvest in November.

Results of TNC in rhizomes of this experiment were close to those reported by Curt et al. (33.6%) [21] and Steinbachová-Vojtíšková et al. (25%) in cattail plants that grew in oligotrophic conditions, but lower than in the work by Martin (61.5%).

According to Escutia-Lara et al. [44], TNC in the youngest parts of rhizomes increases with higher availability of nutrients, and both P and N are important for the accumulation of TNC in rhizomes and roots. Thus, a high P level increases the starch content in rhizomes [44]. On the other hand, Steinbachová-Vojtíšková et al. showed that a good supply of N supports cattail growth and allows greater amounts of storage carbohydrates to accumulate directly in rhizomes for plant growth in the next season [43]. Therefore, the low TNC values obtained in our study can be attributed to little nutrient availability in our experiment, due to the impossibility of carrying out the schedule of fertilization in the GFFs system during the stage of greatest plant growth (March-June 2020), motivated by COVID-19 mobility restrictions.

Several authors have shown that *Typha* is a plant rich in starch [40,41,45], becoming a promising source of renewable glucose for bioethanol production. In this study, the starch content of the rhizomes was 24.0% on dry mass basis, while in roots values reached 15.3% (Fig. 4). These values were close to the ones reported by Curt et al. [21] and Steinbachová-Vojtíšková et al. [43] but much lower than the results obtained by other authors, 40% by Martin [41], 66% by Syed et al. [45] and 70% by Kurzawska et al [20] (Table V). In the studies by Syed et al. and Martin, stumps were analyzed jointly with the rhizomes.

**Table V:** Comparison of the starch content in the rhizomes of the different *Typha* species according to the biomass harvest date. Rh: rhizomes. Stu: stumps

| Species | Biomass fraction | % St | Harvest date | Reference |
|---|---|---|---|---|
| *T. domingensis* | Rh | 24.0 | Nov-2020 | This study |
| *T. domingensis* | Rh | 26.2 | Feb-2019 | [21] |
| *T. latifolia* | Rh + stu | 45.3 | Nov-1977 | [39] |
| *T. latifolia* | Rh+ stu | 40.1 | Nov-1986 | [41] |
| *T. latifolia* | Rh | 70.0 | Jun-2012 | [20] |
| *T. angustifolia* | Young rh | 20.0 | Aug-2005 | [43] |
| *T. angustifolia* | Rh + stu | 66.0 | ------ | [45] |

## 4 CONCLUSIONS

The total biomass of *T. domingensis* grown in a GFF system presents a high energy content (18.7 MJ $kg^{-1}$ $HHV_0$). The ash content of the aerial biomass does not make it an optimal feedstock for combustion applications; however, it could be mixed with other feedstocks with low ash content to produce pellets complying standards or be subjected to other thermochemical processes, such as low-temperature pyrolysis. Moreover, rhizomes of *T. domingensis*, as starch-storing plant organs, can be valorized for starch-based ethanol production.

In the present study, the starch content was lower than expected due to low nutrient availability in the growth medium, as a result of the impossibility of adding fertilizers during the period of highest growth rate of cattails; the literature review shows that rhizomes of *Typha* species may contain up to 70% starch. Therefore, a separate (or selective) harvest of the different plant fractions of *T. domingensis* is recommended according to the subsequent use of each fraction, either as solid or liquid biofuel. Further studies would be needed to assess the feasibility of this proposal.

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