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# Plant Microbial Fuel Cells in a botanical perspective: Nomenclatural constraints and new insights on plant traits potentially affecting bioelectrical perfomance

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ABSTRACT

Plant microbial fuel cells represent an innovative type of microbial fuel cell technology, utilizing plant rhizodeposition to fuel electrochemically active bacteria on the anode surface, thereby generating bioelectricity. This study delves into some botanical aspects of plant species employed in PMFCs and Constructed Wetland PMFCs, aiming to investigate whether their bioelectrical performance is influenced by Raunkiær life forms and root architecture. Our study involved 40 plant species described in 38 documents. In some cases, nomenclature issues prevented the interpretation of actual species used in the experiments. The bioelectrical performance of PMFCs appeared to be significantly affected by both life forms and root architecture. Therophytes and Hemicriptophytes exhibited higher median values than the other life forms, while the Geophyte group showed very high power density values despite a lower median value. In contrast, CW-PMFCs do not appeared to be significantly affected by the botanical traits considered, likely due to the limited data collected on this experimental configuration. The plant species that performed the best in PMFCs include *Carex hirta*, *Alisma plantago-aquatica*, *Glyceria maxima* and *Canna indica*, all of which have an adventitious root system. *C. hirta*, *G. maxima* and *C. indica* are geophytes, while *A. plantago-aquatica* is a hydrophyte. Consequently, epiphytes, chamaephytes and nanophanerophytes, as well as plants with fibrous root systems, appeared to be not recommended for PMFCs. Nevertheless, the results of our study may have certain limitation due to nomenclature issues that prevented the accurate identification of species used in the PMFCs, the absence of a standardized benchmark for electrical measurement, and the lack of clear match between each species and its bioelectrical performance, reducing the data pool.

Abbreviation table

| | |
|---|---|
| EAB | Electrochemically Active Bacteria |
| MFC | Microbial Fuel Cell |
| PMFC | Plant Microbial Fuel Cell |
| CW-PMFC | Constructed Wetland-Plant Microbial Fuel Cell |

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## 1. Introduction

Conventional non-renewable sources of energy have been extensively exploited to meet energy demands [1], significantly contributing to the current energy crisis. The diminishing availability of fossil fuels, along with their impact on climate and the environment, underscores the urgent need to seek alternative energy sources [2]. Plant microbial fuel cells (hereafter PMFCs) represent a promising biotechnology in the context of energy harvesting and are currently under study in many countries [3].

PMFCs are a derivative technology of microbial fuel cells (MFCs) and consist of a plant and two electrodes: one anode coupled to a cathode, with or without a membrane in between, as schematically represented in Fig. 1. ***(Separate file provided, color should be used)***

They utilize plant rhizodeposition (organic compounds released from plant roots into the soil) as nourishment for the electrochemically active bacteria (EAB) growing on the anode surface, thereby enabling the generation of bioelectricity [4]. While plants absorb energy from the environment (e.g., light and $CO_2$) and convert it into nutrients, a portion of these nutrients is released into the soil, and serves as sustenance for the bacteria. EAB, through anaerobic degradation (an oxidative process) occurring on the surface of the anode, release electrical charges into the soil in the form of ions and electrons. These electrons are then transferred to the cathode, generating electricity.

This technology can potentially provide unlimited energy since it is completely self-sufficient. However, many challenges must be addressed before it can be applied on a large-scale [5], such as the stability and power of electrical performance, the standardization of working conditions [5], the quantity of rhizodeposition and the selection of plant species [1].

Selecting the appropriate plant species can enhance bioelectrical performance. Ideal criteria for plant selection may include plant hardiness, growth rate, the microbial community at the rhizosphere, the extensiveness of the root system, adaptability, etc. [4,6]. For example, plant species with C4 photosynthetic pathways are generally preferred in PMFCs because they exhibit high rates of solar energy conversion and high photosynthetic efficiency, leading to increased rhizodeposition that serves as a substrate for microbial oxidation [4]. Initially, PMFCs were restricted to aquatic plants and indoor plants; the first proposed and tested PMFCs were developed by planting the graminoid *Glyceria maxima* Hartm. et Holmb. at the anode of a sediment microbial fuel cell [7]. However, over the last 15 years, this technology has gradually extended to terrestrial plants [3].

Recent reviews have primarily focused on technological and electrochemical issues [1,6], variability in configuration and applications [4,5,8–10], microbiological aspects [1,8,10] and a bibliometric analysis [3]. Botanical aspects were also considered, mainly focusing on photosynthetic pathways, the rhizosphere and soil type [1,5,6,8], with plant species selection primarily based on availability rather than an in-depth knowledge of their physiology [9].

One of the most overlooked aspects concerns the names reported in papers on PMFCs, which are often incorrect, making it difficult to trace the actual species tested.

In this study, we examined the nomenclature and characteristics (plant traits) of various plant species used in PMFCs, which have been little, or not at all, investigated in previous reviews. Specifically, we analyzed life forms and root types as plant traits.

Life forms, according to the Raunkiær system [11], categorize plants based on the location of their growth point during adverse season, which gives them the ability to survive hostile conditions. Depending on the region, the unfavorable period can be the cold winter or the dry summer. In Europe, the growth point during the unfavorable season usually corresponds to winter buds.

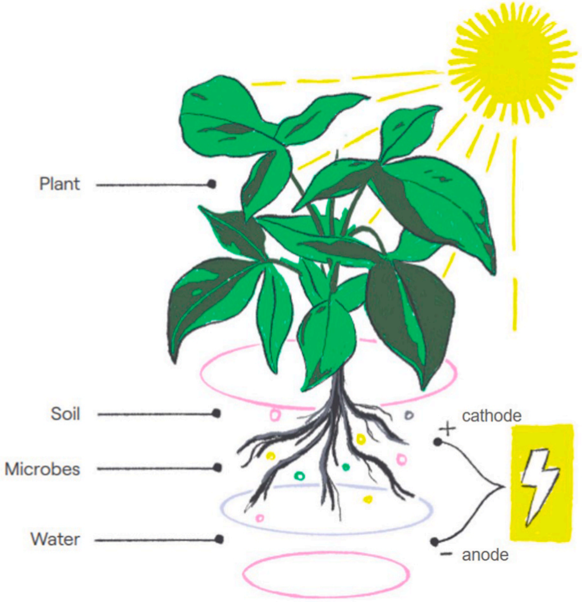

**Fig. 1.** A schematic representation of a PMFC (Plant Microbial Fuel Cell).

Raunkiær life forms include: Epiphytes (which grow attached to other living plants), Phanerophytes (with the growth point in the unfavorable season at least 50 cm above ground level, often on stems), Nanophanerophytes (with the growth point in the unfavorable season from about 25 to 50 cm above ground level) Chamaephytes (with the growth point in the unfavorable seasons up to about 25 cm above ground level), Hemicryptophytes (with the growth point in unfavorable season at or just below the ground level), Therophytes (which survive adverse season as seeds), Cryptophytes or Geophytes (with the growth point in the unfavorable season below ground level), Helophytes (with the growth point - winter buds - below water, and flowering parts above water) and Hydrophytes (water plants). Life forms express the plant's life cycle and their biomass persistence over one or more years: Therophytes are annual species that persist for only few months each year; Hemicryptophytes are herbaceous perennial species that persist for several years, generally with vegetative parts throughout the year; Geophytes/Helophytes/Hydrophytes are herbaceous perennial species that persist for several years, generally with vegetative parts during only part of the year; Chamaephytes are perennial herbaceous/lignified species; Nanophanerophytes and Phanerophytes are woody perennial species, both persisting for several years and with green biomass during all or part of the year (depending on whether they are evergreen or not). These differences in biomass growth and persistence can influence bioelectrical performance in PMFCs experiments.

Root types reflect the extensiveness and complexity of the root system (around which microbial community develops) and, therefore, can contribute to the bioelectrical performance of plants.

With this work, we want to focus on the botanical issues crucial for ensuring a well-functioning system, which also serves as a mirror to the functionality of the technology. Specifically, we sought to answer the following questions: 1) How many and what recognizable species have been used in PMFCs? 2) Could life forms affect PMFCs electrical performance? 3) Could root system types affect PMFCs electrical performance? If the answer to questions 2 and 3 are affirmative, this work could help identify useful characteristics that make certain species eligible or recommended for PMFC technological applications.

## 2. Materials and methods

### 2.1. Paper collection

The Scopus database was queried on April 18, 2024, using the search term "plant microbial fuel cell". The publication years were restricted to the decade 2012–2022, and the document type was limited to "Review" [search string: ⟨TITLE-ABS-KEY ("plant microbial fuel cell") AND PUBYEAR >2011 AND PUBYEAR <2023 AND (LIMIT-TO (DOCTYPE, "re"))⟩]. This search yielded a list of 13 documents. Since our focus was on the botanical aspect, we excluded reviews based on engineering, microbiochemical, and waste removal approaches. Relevant reviews were selected [1,3,4,6,8,10] to find original articles describing PMFC experiments, from which we selected papers containing pertinent information on plant species and bioelectrical performance. A list of 51 papers containing relevant information on plant species and bioelectrogenesis was compiled. Only documents written in English were considered. The present work focused on vascular species (Tracheophyta), excluding ferns and mosses (Pteridophyta and Bryophyta). We considered plant species used in Constructed Wetlands PMFCs (CW-PMFCs), and PMFCs, where plants serve as the fuel to power electrical performance.

### 2.2. Plant nomenclature

The names of all plants cited in the selected papers were verified on Plants of the World Online [12] and, when necessary, cross-referenced with the Flora of a Country within the native distribution range of the species considered [13–17].

### 2.3. Bioelectrical data collection

Due to the heterogeneity of the data concerning electrical performance, certain species were excluded from further analysis under the following conditions: a) multiple species were tested, but the electrical performance of each individual plant could not be clearly extrapolated; b) the study focused on other aspects, and the electrical performance was not calculated or published; c) only voltage or current values were provided; d) average power values and peak power value were too close; e) power density values were $<0.001$ or $>950$ mW/m$^2$. When multiple measurements were provided for a single species, the highest value was used for further data analysis.

### 2.4. Plant traits

#### 2.4.1. Raunkiær life form

Most Raunkiær life form were verified on Plants of the World Online [12] or in the Flora of a country within the native distribution range of the species considered [13–17].

#### 2.4.2. Root type

Root architecture types were grouped into the following three categories, representative of the structural complexity of the hypogeal apparatus: 1) Taproot (including tuberous and bulbous systems); 2) Adventitious (including stoloniferous and rhizomatous systems); 3) Fibrous (including fasciculate and branched systems). The assignment of categories was based on the "root type architecture" trait verified by a detailed study on TRY (Plant Trait Database) [18], when available for the species, and cross-referenced with the Flora of a country within the native distribution range of the species, or expert based.

### 2.5. Data analysis

For the life forms, Epiphytes, Chamaephytes and Nanophanerophytes, were grouped together as perennial non-herbaceous plants. For each life form, we considered the distribution of power density values of the plants included in that life form, and we compared the life forms to find significant differences in terms of power density. Similarly, for each root architecture type, we considered the distribution of power density values of plants within that type, and compared the root types to find significant difference in terms of power density. Analyses were performed separately for plants used in PMFCs and those used in CW-PMFCs experimental configurations. All analyses (Normality test, Mann-Whithney test for equal medians for two samples, Kruskal-Wallis test for equal medians for several samples and Dunn's post-hoc test with raw values) were performed using the software Past 4.09 [19].

## 3. Results and discussion

### 3.1. Data collection and nomenclature of plants

The literature analysis produced a list of 97 entities belonging to 37 Families [Table 1]. Some uncertain entities reported in the reviews, but not found in the cited original papers, were excluded *a priori* or replaced. *Anisogramma anomala,* an ascomycete plant pathogen reported in Deng et al. review [8], was replaced with *Arundinella anomala*, as used in the cited reference [20]. *Lythrum salicaria*, reported in Rusyn's review [10], without a cited reference, was excluded. *Schismus arabicus*, also reported in Rusyn's review [10], was replaced with "*Sporobolusarabicus",* as used in the cited reference [21].

The following 4 entities identified only at the genus level were excluded: *Carex* sp. [39], *Mentha* sp. [47], *Myriophyllum* sp. [37], *Sansevieria* sp [31].

The nomenclature of species was correct in most remaining cases. However, some nomenclatural issues led to the exclusion of certain species and *ad hoc* assumptions. The first case included species reported with their Latin name but without the author, making it impossible to identify the exact species used for PMFCs: *Lemna minuta* [25], which could be *Lemna minuta* Kunth or *Lemna valdiviana* Phil.; *Scirpus Validus* [43], which could be *Schoenoplectus tabernaemontani* (C.C.Gmel.) Palla, or *Eleocharis geniculata* (L.) Roem. & Schult., or *Schoenoplectus californicus* (C.A.Mey.) Soják; *Festuca arundinaceae* [52], which could be *Lolium arundinaceum* (Schreb.) Darbysh., or *Scolochloa festucacea* (Willd.) Link, or *Festuca rubra* L. Due to this uncertainty, these species were excluded from further analysis.

A second case involved cultivated species or varieties, not always clearly indicated: *Hyacinth* "pink" [30]*,* for which we assumed the valid name *Hyacinthus orientalis* L.; *Canna indica* L. "Stuttgart" [32], for which we assumed the valid name *Canna indica* L.; *Papyrus diffuses* [28]*,* for which we assumed the valid name *Cyperus diffusus* Vahl; *Oryza sativa* spp. *japonica* L. [59], for which we assumed the valid name *Oryza sativa* L.

A third case included reunited species: *Sedum reflexum* and *S. rupestre* were considered different species in the original paper [38], but the updated nomenclature considers them as a unique species, *Petrosedum rupestre* (L.) P.V.Heath (for further analysis, we considered the bioelectrical output *Sedum rupestre*); *Opuntia ficus-indica* and *O. joconostle* were considered different species in the original paper [33], but the updated nomenclature considers them as a single species, *Opuntia ficus-indica* (L.) Mill.

Updated species names, Family, native ranges of the species and geographical areas of experiments are summarized in Table 1 *(separate pages at the end)*.

### 3.2. Data collection about bioelectrical performance

The following 23 species of phanerophytes and lignified shrubs were excluded, as studies on these groups are at their early stages, and limited literature is available [24,33,49]. Moreover, many of them are reported without direct correspondence between the electrical performance and individual species [24]. These included: *Alnus glutinosa*, *Betula pendula*, *Betula pubescens*, *Carpinus betulus*, *Fagus sylvatica*, *Hedera helix*, *Juglans regia*, *Malus domestica* [24], *Opuntia albicarpa*, *Opuntia ficus-indica*, *Opuntia robusta* [33], *Pandanus amaryllifolius* [49], *Pinus sylvestris*, *Prunus cerasus*, *Prunus domestica*, *Pyrus communis*, *Quercus robur*, *Ribes nigrum*, *Ribes rubrum*, *Ribes uva-crispa, Rubus idaeus*, *Viburnum opulus*, and *Vitis vinifera* [24].

Another 27 species were excluded according to the criteria previously listed in "Materials and methods" and described as follows.

The absence of electrical performance clearly related to each single species caused the exclusion of: *Chamaedorea elegans* [24], *Clinopodium nepeta* = *Calamintha nepeta* [39]*, Clivia miniata* = *Vallota miniata* [24]*, Clivia nobilis* [24]*, Crassula ovata* [24]*, Dieffenbachia seguine* [24]*, Epilobium parviflorum* [39]*, Kalanchoe pinnata* = *Bryophyllum pinnatum* [37]*, Lolium perenne* [56]*, Lycopus europaeus* [39], *Marsilea quadrifolia* [39]*, Mentha acquatica* [39]*, Solanum lycopersicum* [37], *Spathiphyllum lanceifolium* [24].

The lack of calculated or published electrical performance caused the exclusion of *Cenchrus setaceus* = *Pennisetum setaceum* [50] and *Chrysopogon nemoralis* = *Vetiveria nemoralis* [51].

The provision of only voltage values or current values caused the exclusion of: *Artemisia fukudo* [27] *Arundo donax* [20]*, Cyperus alternifolius* subsp. *flabelliformis* = *Cyperus involucratus* [42]*, Hydrilla verticillata* [46] also reported in Chiranjeevi et al. [37], but without clearly related electrical perfomance*, Hydrocotyle verticillata* [27]*, Juncus effusus* [43]*, Puccinellia distans* [62].

The similarity between average power values and peak power values caused the exclusion of *Arundinella hirta* = *Arundinella anomala* [20].

Power density values $< 0.001$ or $>950$ mW/m$^2$ led to the exclusion of the following species: *Phedimus kamtschaticus* = *Sedum kamtschaticum* [38]*, Phedimus spurius* = *Sedum spurium* [38]*, Rotala rotundifolia* [48].

**Table 1**
First list of 97 species: Family, updated name, name in the original paper, native range of species, and geographical area of the study.

| Family | Updated Species name | Species name in the original paper | Species native range | Geographical area of study | Reference |
|---|---|---|---|---|---|
| Alismataceae | *Alisma plantago-aquatica* L. | *Alisma plantago-aquatica* | Temp. Eurasia, N. Africa to Tanzania | Ukraine | [22] |
| Amaryllidaceae | *Agapanthus africanus* (L.) Hoffmanns. | *Agapanthus africanus* L. *Hoffman* | SW. Cape Prov | Mexico | [23] |
| | *Clivia miniata* (Lindl.) Verschaff. | *Vallota miniata* Lindl. | S. Africa | Ukraine | [24] |
| | *Clivia nobilis* Lindl. | *Clivia nobilis* Lindl. | E. Cape Prov | Ukraine | [24] |
| Araceae | *Dieffenbachia seguine* (Jacq.) Schott | *Dieffenbachia seguine* (Jacq.) Schott | Somalia to S. Africa, W. Indian Ocean | Ukraine | [24] |
| | *Epipremnum aureum* (Linden & André) G.S.Bunting | *Epipremnum aureum* | Society Islands (Moorea) | India | |
| | - | *Lemna minuta* | – | Bulgaria | [25] |
| | *Pistia stratiotes* L. | *Pistia stratiotes* | Tropics & Subtropics | Philippines | [26] |
| | *Spathiphyllum lanceifolium* (Jacq.) Schott | *Spathiphyllum lanceifolium* (Jacq.) Schott | Colombia to Venezuela | Ukraine | [24] |
| Araliaceae | *Hedera helix* L. | *Hedera helix* L. | Europe to W. & N. Türkiye | Ukraine | [24] |
| | *Hydrocotyle verticillata* Thunb. | *Hydrocotyle verticillata* | New World, Somalia to S. Africa, Madagascar, Caucasus to N. Iran | Japan | [27] |
| Arecaceae | *Chamaedorea elegans* Mart. | *Chamaedorea elegans* Mart. | Mexico to Honduras | Ukraine | [24] |
| Asparagaceae | *Chlorophytum comosum* (Thunb.) Jacques | *Chlorophytum comosum* | W. Tropical Africa to Cameroon, Ethiopia to S. Africa | Algerie | [28] |
| | *Dracaena braunii* Engl. | *Dracaena braunii* | W. Central Tropical Africa (Cameroon, Congo, Equatorial Guinea, Gabon) | India | [29] |
| | *Hyacinthus orientalis* L. | *Hyacinth pink* | CULTIVAR | Ireland | [30] |
| | - | *Sansevieria asparagaceae* | – | Mexico | [31] |
| Asteraceae | *Artemisia fukudo* Makino | *Artemisia fukudo* | China (E. Zhejiang), Korea, Japan (Honshu, Kyushu), N. Taiwan | Japan | [27] |
| Betulaceae | *Alnus glutinosa* (L.) Gaertn. | *Alnus glutinosa* (L.) Gaerth. | Europe to W. Siberia and Iran | Ukraine | [24] |
| | *Betula pendula* Roth. | *Betula pendula* Roth. | Temp. Eurasia, NW. Africa, Alaska to Canada | Ukraine | [24] |
| | *Betula pubescens* Ehrh. | *Betula pubescens* | Newfoundland to Greenland, Europe to Russian Far East and N. Iran | Ukraine | [24] |
| | *Carpinus betulus* L. | *Carpinus betulus* L. | Europe to Iran | Ukraine | [24] |
| Brassicacee | *Brassica juncea* (L.) Czern. | *Brassica juncea* | Caucasus | India | [32] |
| Cactaceae | *Opuntia albicarpa* Scheinvar | *Opuntia albicarpa* | Mexico | Mexico | [33] |
| | *Opuntia ficus-indica* (L.) Mill. | *Opuntia ficus-indica* | Mexico | Mexico | [33] |
| | | *Opuntia joconostle* | | | [33] |
| | *Opuntia robusta* H.L. Wendl. ex Pfeiff. | *Opuntia robusta* | Mexico | Mexico | [33] |
| Cannaceae | *Canna indica* L. | *Canna indica* | Tropical & Subtropical America | USA/China | [34] |
| | | *Canna stuttgart* | CULTIVAR | India | [32] |
| Commelinaceae | *Wachendorfia thyrsiflora* L. | *Wachendorfia thyrsiflora* | Cape Prov | South Africa | [35] |
| Convolvulaceae | *Ipomoea aquatica* Forssk. | *Ipomoea aquatica* Forssk. | Tropical & Subtropical Old World (Africa, Asia, Oceania) | China<br>Philippines | [36]<br>[26] |
| Crassulaceae | *Crassula ovata* (Mill.) Druce | *Crassula ovata* (Miller) Druce (1917) | SE. Mozambique to SE. Cape Prov | Ukraine | [24] |
| | *Kalanchoe pinnata* (Lam.) Pers. | *Bryophyllum pinnatum* | Madagascar | India | [37] |
| | *Petrosedum rupestre* (L.) P.V. Heath | *Sedum rupestre*<br>*Sedum reflexum* | Europe to Türkiye | Chile | [38] |
| | *Phedimus hybridus* (L.) ’t Hart | *Sedum hybridum* | E. European Russia to Siberia and Mongolia | Chile | [38] |
| | *Phedimus kamtschaticus* (Fisch.) ’t Hart | *Sedum kamtschaticum* Fisch. & Mey. | Russian Far East to N. China and N. Japan | Chile | [38] |
| | *Phedimus spurius* (M.Bieb.) ’t Hart | *Sedum spurium* M. Bieb. | NE. Türkiye to N. Iran | Chile | [38] |
| | *Sedum album* L. | *Sedum album* | Europe to Medit. and NW. Iran | Chile | [38] |
| | *Sedum sexangulare* L. | *Sedum sexangulare* | Europe | Chile | [38] |
| Cyperaceae | - | *Carex* sp. | – | Italy | [39] |
| | *Carex divisa* Huds. | *Carex divisa* HUDSON | Europe to W. China | Turkey | [40] |
| | *Carex hirta* L. | *Carex hirta* | Europe to Iran, N. Africa | Ukraine | [41] |
| | *Cyperus alternifolius* subsp. *flabelliformis* Kük. | *Cyperus involucratus* Rottb. | Tropical Africa, KwaZulu-Natal, Madagascar, Arabian Peninsula | Thailand | [42] |
| | *Cyperus diffusus* Vahl | *Papyrus diffusus* | CULTIVAR | Algerie | [28] |
| | *Cyperus prolifer* Lam. | *Cyperus prolifer* | Somalia to S. Africa, W. Indian Ocean | South Africa | [35] |
| | *Rhynchospora colorata* (L.) H.Pfeiff. | *Rhynchospora colorata* | SE. U.S.A. to N. South America | Japan | [27] |
| | - | *Scirpus validus* Benth. | – | China | [43] |

(*continued on next page*)

**Table 1** (*continued*)

| Family | Updated Species name | Species name in the original paper | Species native range | Geographical area of study | Reference |
|---|---|---|---|---|---|
| Fabaceae | *Trigonella foenum-graecum* L. | *Trigonella foenum-graecum* | Iraq to N. Pakistan | India | [32] |
| | *Vigna radiata* (L.) R.Wilczek | *Vigna radiata* Wilzeck | Arabian Peninsula, Taiwan to Tropical Asia and N. & E. Australia | Philippines | [44] |
| Fagaceae | *Fagus sylvatica* L. | *Fagus sylvatica* L. | Europe to Caucasus | Ukraine | [24] |
| | *Quercus robur* L. | *Quercus robur* L. | Europe to Iran | Ukraine | [24] |
| Grossulariaceae | *Ribes nigrum* L. | *Ribes nigrum* L. | Europe to Russian Far East and Central Asia | Ukraine | [24] |
| | *Ribes rubrum* L. | *Ribes rubrum* L. | W. Europe | Ukraine | [24] |
| | *Ribes uva-crispa* L. | *Ribes uva-crispa* L. | Europe, NW. Africa, NE. Türkiye to N. Iran | Ukraine | [24] |
| Haloragaceae | – | *Myriophyllum* sp. | – | India | [37] |
| Hydrocharitaceae | *Elodea nuttallii* (Planch.) H. St.John | *Elodea nuttalii* | S. Canada to U.S.A | Malaysia | [45] |
| | *Hydrilla verticillata* (L.f.) Royle | *Hydrilla verticillata* | Poland to Asia, Australia, Uganda to N. Zambia | India<br>China | [37]<br>[46] |
| Iridaceae | *Chasmanthe floribunda* (Salisb.) N.E.Br. | *Chasmanthe floribunda* | W. & SW. Cape Prov | Algerie | [28] |
| | *Iris pseudacorus* L. | *Iris pseudacorus* | Europe to Caucasus, Medit. to Iran | Ireland | [30] |
| Juglandaceae | *Juglans regia* L. | *Juglans regia* L. | NE. & E. Türkiye to Lebanon and W. Himalaya | Ukraine | [24] |
| Juncaceae | *Juncus effusus* L. | *Juncus effuses* | Temp. Northern Hemisphere to W. South America, Rwanda to S. Africa, W. Indian Ocean | China | [43] |
| | *Juncus gerardi* Loisel. subsp. *gerardi* | *Juncus gerardii* Loisel. subsp. gerardii | Europe, Medit. to Mongolia, Canada to N. U.S.A. | Turkey | [40] |
| Lamiaceae | *Clinopodium nepeta* (L.) Kuntze | *Calamintha nepeta* L. | Central Europe, Medit., N. Iran | Italy | [39] |
| | *Lycopus europaeus* L. | *Lycopus europaeus* L. | Azores, Europe to China | Italy | [39] |
| | - | *Mentha* sp. L. | – | Italy | [47] |
| | *Mentha acquatica* L. | *Mentha acquatica* L. | Africa, Europe to Central Siberia and W. Asia | Italy | [39] |
| Lythraceae | *Rotala rotundifolia* (Buch.-Ham. ex Roxb.) Koehne | *Rotala rotundifolia* | India to Temp. E. Asia | Taiwan | [48] |
| Marsileaceae | *Marsilea quadrifolia* L. | *Marsilea quadrifolia* L. | Canary Islands, Europe to Japan and Iran | Italy | [39] |
| Onagraceae | *Epilobium parviflorum* Schreb. | *Epilobium parviflorum* Schreb. | Temp. Eurasia | Italy | [39] |
| Pandanaceae | *Pandanus amaryllifolius* Roxb. ex Lindl. | *Pandanus amaryllifolius* | Maluku | Malaysia | [49] |
| Pinaceae | *Pinus sylvestris* L. | *Pinus silvestris* L. | Europe to Russian Far East and Caucasus | Ukraine | [24] |
| Poaceae | *Arundinella hirta* (Thunb.) Tanaka | *Arundinella anomala* | S. Siberia, Temp. E. Asia and N. Indo-China | Netherlands | [20] |
| | *Arundo donax* L. | *Arundo donax* L. | W. & Central Asia, Temp. E. Asia | Netherlands | [20] |
| | *Cenchrus alopecuroides* (L.) Thunb. | *Pennisetum alopecuroides* | China to Temp. E. Asia and W. & Central Malesia, NW. & E. Australia | Taiwan | [48] |
| | *Cenchrus setaceus* (Forssk.) Morrone | *Pennisetum setaceum* | N. Africa to Afghanistan and Tanzania | India | [50] |
| | *Chrysopogon nemoralis* (Balansa) Holttum | *Vetiveria nemoralis* A. | Indo-China to Philippines (Panay) | Thailand | [51] |
| | *Chrysopogon zizanioides* (L.) Roberty | *Vetiveria zizaniodes* Nash | Indo-China to Malesia | Ukraine | [51] |
| | *Cynodon dactylon* (L.) Pers. | *Cynodondactylon* | Temp. & Subtropical Old World to Australia | Pakistan | [21] |
| | **-** | *Festuca arundinacea* | – | Ukraine | [52] |
| | *Glyceria maxima (*Hartm.) Holmb. | *Glyceria maxima* | Europe to Xinjiang | Netherlands<br>Netherlands<br>Netherlands<br>Netherlands | [7]<br>[53]<br>[54]<br>[55] |
| | *Lolium perenne* L. | *Lolium perenne* | Macaronesia, N. Africa, Europe to Siberia and Himalaya | China | [56] |
| | *Oryza sativa* L. | *Oryza sativa* L. | China | Japan<br>Australia<br>Italy | [57]<br>[58]<br>[39] |
| | | *Oryza sativa* spp. *Japonica* cultivar Koshihirari | CULTIVAR | Japan | [59] |
| | *Phragmites australis* (Cav.) Trin. Ex Steud. | *Phragmites australis* | Temp. & Subtropical to Tropical Mountains | Japan<br>South Africa<br>Netherlands | [27]<br>[35]<br>[60] |

(*continued on next page*)

**Table 1** (*continued*)

| Family | Updated Species name | Species name in the original paper | Species native range | Geographical area of study | Reference |
|---|---|---|---|---|---|
| | | | | Netherlands | [61] |
| | | | | Ireland | [30] |
| | *Puccinellia distans* (Jacq.) Parl. | *Puccinellia distans* (Jacq.) Parl. | Subarctic to Temp. Eurasia | Canada | [62] |
| | *Sporobolus anglicus* (C.E. Hubb.) P.M.Peterson & Saarela | *Spartina anglica* | NE. Türkiye to N. Iran | Netherlands | [20] |
| | | | | Netherlands | [63] |
| | | | | Netherlands | [64] |
| | | | | Netherlands | [60] |
| | | | | Netherlands | [65] |
| | | | | Netherlands | [61] |
| | *Sporobolus ioclados* (Nees ex Trin.) Nees | *Sporobolasarabicus* | Africa to Indian Subcontinent | Pakistan | [21] |
| Pontederiaceae | *Pontederia crassipes* Mart. | *Eichhornia crassipes* | S. Tropical America | Philippines | [66] |
| Ranunculaceae | *Caltha palustris* L. | *Caltha palustris* L. | Temp. & Subarctic Northern Hemisphere | Ukraine | [67] |
| Rosaceae | *Malus domestica* (Suckow) Borkh. | *Malus domestica* Borkh. | Afghanistan to Central Asia and Xinjiang | Ukraine | [24] |
| | *Prunus cerasus* L. | *Prunus cerasus* L. | Caucasus | Ukraine | [24] |
| | *Prunus domestica* L. | *Prunus domestica* L. | Transcaucasus to N. Iran | Ukraine | [24] |
| | *Pyrus communis* L. | *Pyrus communis* L. | Europe to N. Iraq | Ukraine | [24] |
| | *Rubus idaeus* L. | *Rubus idaeus* L. | Temp. Northern Hemisphere to Mexico | Ukraine | [24] |
| Solanaceae | *Solanum lycopersicum* L. | *Solanum lycopersicum* | Peru | India | [37] |
| Typhaceae | *Typha angustifolia* L. | *Typha angustifolia* | Temp. Northern Hemisphere | Taiwan | [48] |
| | | | | Turkey | [40] |
| | *Typha domingensis* Pers. | *Typha domingensis* Pers. | Tropics & Subtropics | Mexico | [68] |
| | *Typha latifolia* L. | *Typha latifolia* L. | Temp. Northern Hemisphere to Colombia, W. Bolivia to S. South America, Nigeria to Kenya | Malaysia | [69] |
| | | | | Turkey | [40] |
| | *Typha orientalis* C.Presl | *Typha orientalis* | Mongolia to Japan and Philippines, Australasia | China | [43] |
| Viburnaceae | *Viburnum opulus* L. | *Viburnum opulus* L. | Europe to Siberia and Türkiye, N. Algeria | Ukraine | [24] |
| Vitaceae | *Vitis vinifera* L. | *Vitis vinifera* L. | S. Central & SE. Europe to Central Asia and N. Iran | Ukraine | [24] |

The most reasonable value to consider would be the volumetric power density expressed as $mW/m^3$. However, since the produced energy does not increase indefinitely with volume for a given plant/soil system, the area can be considered the real parameter characterizing the interface between plant and soil. Moreover, most of the data reported in the considered literature were expressed as $mW/m^2$, so we used this unit for our elaboration.

When multiple measurements were provided for a single species, we considered the highest value for further data analysis. *Canna indica* was used by Lu et al. [34] in CW-PMFCs and Sophia and Sreeja [32] in PMFCs experiments, the latter obtaining the highest bioelectrical output. *Glyceria maxima* was used in several PMFCs experiments [7,53–55], with Timmers et al. [54] obtaining the highest bioelectrical output. *Ipomoea aquatica* was used by Liu et al. [36] in CW-PMFCs and by Pamintuan et al. [26] in PMFCs experiments, with the former achieving the highest bioelectrical output. *Oryza sativa* was used in several PMFC experiments [39,59,57,58], with Goto et al. [59] obtaining the highest bioelectrical output. *Phragmites australis* was used in several PMFC [27,60,61] and CW-PMFC [30,35] experiments, with Oodally et al. [35] obtaining the highest bioelectrical output. *Sporobolus anglicus* = *Spartina anglica* was used in several PMFC experiments [20,60,61,63–65], with Wetser et al. [65], obtaining the highest bioelectrical output. *Typha angustifolia* was used by Guan and Yu [48] in PMFCs and by Saz et al. [40] in CW-PMFC experiments, with the latter obtaining the highest bioelectrical output. *Typha latifolia* was used by Oon et al. [69] and Saz et al. [40] in CW-PMFC experiments, with the latter obtaining the highest bioelectrical output.

Finally, we were able to provide a power density value ($mW/m^2$) for 40 species, comprising 28 species used in PMFCs and 12 species used in CW-PMFCs.

Their scientific name, experimental configuration, electrical output, life form and root type are summarized in Table S.1 in Supplementary material.

## 3.3. Raunkiær life forms

### 3.3.1. Raunkiær life forms in PMFCs

We compared the distribution of power density values among plant species used in PMFCs, according to their life forms. Therophytes (T) included *Brassica juncea* [32], *Oryza sativa* [59], *Trigonella foenum-graecum* [32], and *Vigna radiata* [44].

Hemicriptophytes (H) included *Caltha palustris* [67], *Cenchrus alopecuroides* = *Pennisetum alupecuroides* [48], *Sporobolus anglicus* [65], and *Sporobolus ioclados* = *Sporobolus arabicus* [21].

Geophytes (G) included *Agapanthus africanus* [23], *Canna indica* [32], *Carex hirta* [41], *Chasmanthe floribunda* [28], *Chlorophytum comosum* [28], *Cynodon dactylon* [21], *Cyperus diffusus* [28], *Glyceria maxima* [54], *Rhynchospora colorata* [27], and *Typha domingensis*

[68]. Helophytes/Hydrophytes (He/Hy) included *Chrysopogon zizaniodes* = *Vetiveria zizaniodes* [51] and *Pistia stratiotes* [26] as helophytes; *Alisma plantago-acquatica* [22] and *Pontederia crassipes* = *Eichhornia crassipes* [66] as hydrophytes.

Epiphytes/Chamaephytes/Nanophanerophytes (Ep/Ch/NP) included *Epipremnum aureum* [29] as epiphyte; *Petrosedum rupestre*, *Phedimus hybridus* = *Sedum hybridum*, *Sedum album*, and *Sedum sexangulare* [38] as chamaephytes; *Dracaena braunii* [29] as Nanophanerophyte.

The distributions of power density values for each life form category were found to be non-normal, except for Therophytes. We therefore conducted the Kruskal-Wallis non-parametric test for equal medians and followed it with Dunn's Post-hoc test using raw values. The Kruskal-Wallis test indicated no significant differences among the groups [$H$ ($chi^2$): 7.896; $H_c$ (tie-corrected): 7.896; $p$ (same): 0.09548]. However Dunn's Post-hoc test revealed significant differences between the Ep/Ch/NP and G groups (raw $p$ value = 0.01006), and among Ep/Ch/NP and T groups (raw $p$ value = 0,04133). Violin plots representing the distribution of power density values **[Fig. 2a]** *(Separate file provided, color should be used)* illustrate that Therophytes and Hemicriptophytes have comparable median values, which are higher than those of other life forms. Despite the low median value, the Geophyte group includes an outlier with a very high power density value (*Carex hirta* = 950 mW/m$^2$).

### 3.3.2. Raunkiær life forms in CW-PMFCs

We also compared the distribution of power density values among plant species used in CW-PMFCs according to their life forms. Geophytes (G) included *Carex divisa* Huds. [40], *Cyperus prolifer* Lam. [35], *Hyacinthus orientalis* L., *Iris pseudacorus* L. [30], *Juncus gerardi* Loisel. subsp. gerardi [40], *Phragmites australis* (Cav.) Trin. ex Steud. [35], *Typha angustifolia* L. [40], *Typha latifolia* L. [40], and *Wachendorfia thyrsiflora* L [35]. Helophytes/Hydrophytes (He/Hy) included *Ipomoea aquatic*a Forssk [36]. and *Typha orientalis* C.Presl [43]as helophytes; *Elodea nuttalii* (Planch.) H.St.John [45] as hydrophyte.

The distribution of power density values of Geophytes was non-normal. Given that the samples were only two, we used the Mann-Whitney non-parametric test for equal medians, which returned no significant differences between the groups [$p$ (same): 0.6]. Violin plots representing the distribution of power density values show that the medians of the two groups do not differ **[Fig. 2b]** . *(Separate file provided, color should be used)*

Plant species, categorized by life form for each experimental configuration (PMFCs an CW-PMFCs), and arranged in order of decreasing power density for each category, are summarized in Table 2. *(Separate pages at the end)*.

## 3.4. Root system type

### 3.4.1. Root system type in PMFCs

We compared the distribution of power density values of plant species grouped by root system type used in PMFCs**.** Taproot group included *Chasmante floribunda*, *Cholorophytum comosum*, *Brassica juncea* and *Trigonella foenum-graecum*. Adventitous group included *Agapanthus africanus*, *Canna indica*, *Carex hirta*, *Cynodon dactylon*, *Cyperus diffusus*, *Glyceria maxima*, *Rhynchospora colorata*, *Typha domingensis*, *Caltha palustris*, *Sporobolus anglicus*, *Sporobolus ioclados*, *Alisma plantago-aquatica*, *Epipremnum aureum* and *Dracaena braunii*. Fibrous group included *Cenchrus alopecuroides*, *Oryza sativa*, *Vigna radiata*, *Chrysopogon zizanioides*, *Pistia stratiotes*, *Pontederia crassipes*, *Petrosedum rupestre*, *Phedimus hybridus*, *Sedum sexangulare*.

The distributions of power density values were non-normal, except for Taproot group. Therefore, we performed the Kruskal-Wallis non-parametric test for equal medians, followed by Dunn's Post-hoc test using raw values. Kruskal-Wallis test indicated a significant difference among groups [$H$ ($chi^2$): 8.758; $H_c$ (tie corrected): 8.758; $p$ (same): 0.01254]. Dunn's Post-hoc test revealed significant differences between the Adventitious and Fibrous groups (raw p value = 0,003461). Violin plots representing the distributions of

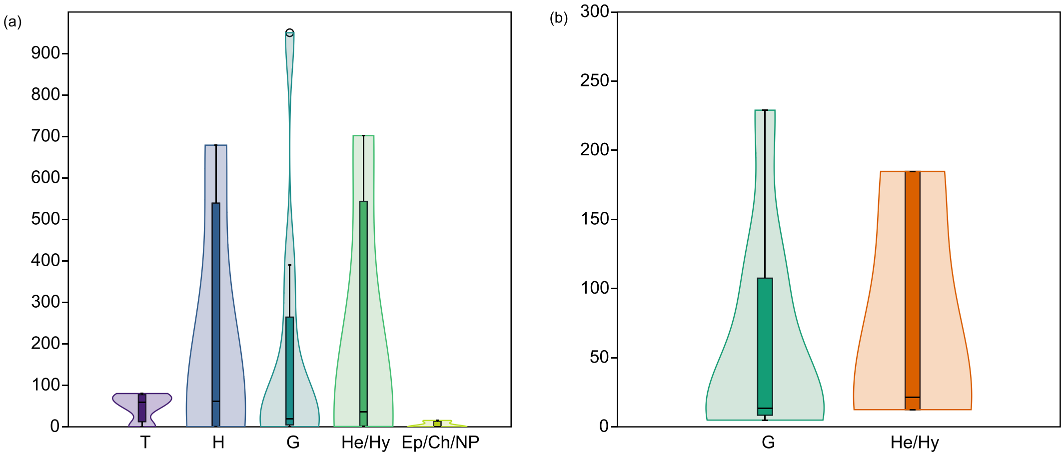

**Fig. 2.** Violin plot representation of the power density distributions of life forms used in PMFCs **(a)** and CW-PMFCs **(b)**. T = Therophytes; H = Hemycriptophytes, G = Geophytes, He/Hy = Helophytes/Hydrophytes, Ep/Ch/NP = Epiphytes/Chamaephytes/Nanophanerophytes.

**Table 2**
Plant species divided by Life form for each Experimental configuration (PMFCs an CW-PMFCs), arranged in order of decreasing power density for each category.

| Experimental configuration | Life Form | Updated Species name | Maximum Power density mW/m$^2$ |
|---|---|---|---|
| PMFC | Geophytes | *Carex hirta* L. | 950 |
| | | *Glyceria maxima* (Hartm.) Holmb. | 390 |
| | | *Canna indica* L. | 222,54 |
| | | *Cynodon dactylon* (L.) Pers. | 58 |
| | | *Rhynchospora colorata* (L.) H.Pfeiff. | 20 |
| | | *Chlorophytum comosum* (Thunb.) Jacques | 18 |
| | | *Agapanthus africanus* (L.) Hoffmanns. | 15,55 |
| | | *Typha domingensis* Pers. | 6,12 |
| | | *Cyperus diffusus* Vahl | 1083 |
| | | *Chasmanthe floribunda* (Salisb.) N.E.Br. | 0,21 |
| | Hydrophytes | *Alisma plantago-aquatica* L. | 702 |
| | | *Pontederia crassipes* Mart. | 0,86 |
| | Helophytes | *Chrysopogon zizanioides* (L.) Roberty | 68 |
| | | *Pistia stratiotes* L. | 3,54 |
| | Hemycriptophytes | *Sporobolus anglicus* (C.E.Hubb.) P.M.Peterson & Saarela | 679 |
| | | *Sporobolus ioclados* (Nees ex Trin.) Nees | 120 |
| | | *Cenchrus alopecuroides* (L.) Thunb. | 2,86 |
| | | *Caltha palustris* L. | 0,18 |
| | Terophytes | *Trigonella foenum-graecum* L. | 80,26 |
| | | *Brassica juncea* (L.) Czern. | 69,32 |
| | | *Oryza sativa* L. | 49 |
| | | *Vigna radiata* (L.) R.Wilczek | 0,35 |
| | Epiphytes | *Epipremnum aureum* (Linden & André) G.S.Bunting | 15,38 |
| | Nano-Phanerophytes | *Dracaena braunii* Engl. | 12,78 |
| | Chamaephytes | *Phedimus hybridus* (L.) 't Hart | 0,092 |
| | | *Petrosedum rupestre* (L.) P.V.Heath | 0,0155 |
| | | *Sedum sexangulare* L. | 0,0084 |
| | | *Sedum album* L. | 0,0024 |
| Constructed Wetlands MFC | Geophytes | *Cyperus prolifer* Lam. | 229 |
| | | *Phragmites australis* (Cav.) Trin. Ex Steud. | 109 |
| | | *Wachendorfia thyrsiflora* L. | 106 |
| | | *Typha angustifolia* L. | 18,1 |
| | | *Typha latifolia* L. | 13,4 |
| | | *Iris pseudacorus* L. | 13,27 |
| | | *Carex divisa* Huds. | 8,8 |
| | | *Juncus gerardi* Loisel. subsp. *gerardi* | 8,1 |
| | | *Hyacinthus orientalis* L. | 4,86 |
| | Hydrophytes | *Elodea nuttallii* (Planch.) H.St.John | 184,75 |
| | Helophytes | *Typha orientalis* C.Presl | 21,53 |
| | | *Ipomoea aquatica* Forssk. | 12,42 |

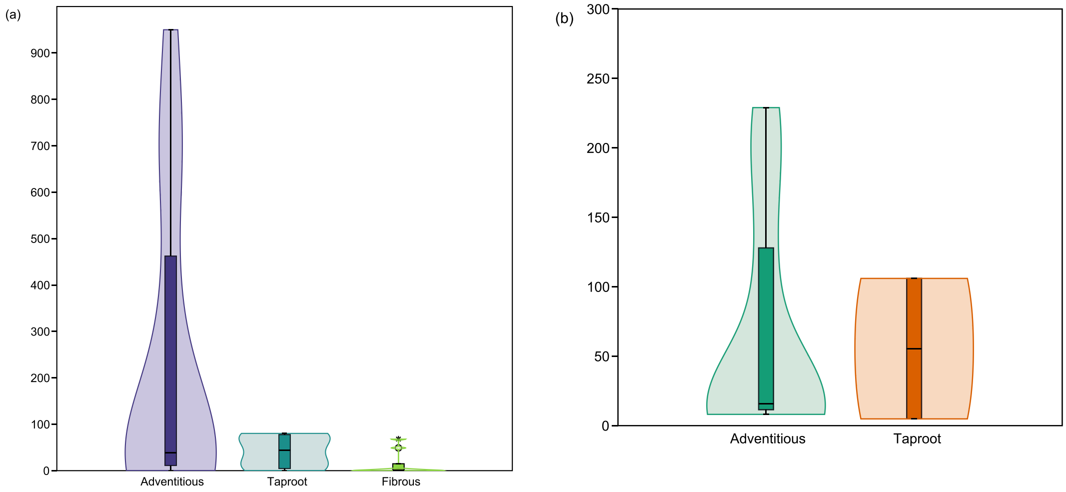

**Fig. 3.** Violin plot representation of power density distributions of root types used in PMFCs **(a)** and CW-PMFCs **(b)**.

power density values **[Fig. 3a]** *(Separate file provided, color should be used)* show comparable median values for Taproot and Adventitious groups, with the Adventitious exhibiting the widest distribution, while the Taproot group presents more condensed values.

### *3.4.2. Root system type in CW-PMFCs*

We compared the distribution of power density values of plant species grouped by root system type and used in CW-PMFCs. Taproot include *Hyacinthus orientalis* and *Wachendorfia thyrsiflora*. Adventitous included *Carex hirta*, *Cyperus prolifer*, *Iris pseudacorus*, *Juncus gerardi* subsp. *gerardi*, *Phragmites australis*, *Typha angustifolia*, *Typha latifolia*, *Ipomoea acquatica*, *Typha orientalis*, and *Elodea nuttalii*. The distribution of power density values for Adventitious plants was non-normal. Given that the samples are only two, we used Mann-Whitney non-parametric test for equal medians, which returned no significant differences between the groups [*p(*same): 0.59] Violin plots representing the distribution of power density values show a higher median value for Taproot than for Adventitious root system **[Fig. 3b]** . *(Separate file provided, color should be used)*

Plant species, categorized by root system type for each experimental configuration (PMFCs an CW-PMFCs), arranged in order of decreasing power density for each category, are summarized in Table 3. *(Separate pages at the end)*.

## 4. Conclusions

Our results allow us to address the questions posed in the introduction. The nomenclature analysis of *taxa* used in PMFCs resulted in a list of 90 identifiable species, including 23 Phanerophytes and lignified shrubs, and other 67 other vascular plants. However only 40 species were used for statistical analysis due to the limitations related to their electrical performance.

For 7 *taxa* reported in the literature, it was not possible to accurately identify the species and therefore the associated traits. Additionally, for 50 *taxa*, valid bioelectrical output values could not be obtained, reducing the dataset available for analysis by more

**Table 3**
Plant species divided by Root type for each Experimental configuration (PMFC and CW-PMFC), arranged in order of decreasing power density for each category.

| Experimental configuration | Root Type | Updated Species name | Maximum Power density mW/m$^2$ |
|---|---|---|---|
| PMFC | Adventitious | *Carex hirta* L. | 950 |
| | | *Alisma plantago-aquatica* L. | 702 |
| | | *Sporobolus anglicus* (C.E.Hubb.) P.M.Peterson & Saarela | 679 |
| | | *Glyceria maxima (*Hartm.) Holmb. | 390 |
| | | *Canna indica* L. | 222,54 |
| | | *Sporobolus ioclados* (Nees ex Trin.) Nees | 120 |
| | | *Cynodon dactylon* (L.) Pers. | 58 |
| | | *Rhynchospora colorata* (L.) H.Pfeiff. | 20 |
| | | *Agapanthus africanus* (L.) Hoffmanns. | 15,55 |
| | | *Epipremnum aureum* (Linden & André) G.S.Bunting | 15,38 |
| | | *Dracaena braunii* Engl. | 12,78 |
| | | *Typha domingensis* Pers. | 6,12 |
| | | *Cyperus diffusus* Vahl | 1083 |
| | | *Caltha palustris* L. | 0,18 |
| | Taproot | *Trigonella foenum-graecum* L. | 80,26 |
| | | *Brassica juncea* (L.) Czern. | 69,32 |
| | | *Chlorophytum comosum* (Thunb.) Jacques | 18 |
| | | *Chasmanthe floribunda* (Salisb.) N.E.Br. | 0,21 |
| | Fibrous | *Chrysopogon zizanioides* (L.) Roberty | 68 |
| | | *Oryza sativa* L. | 49 |
| | | *Pistia stratiotes* L. | 3,54 |
| | | *Cenchrus alopecuroides* (L.) Thunb. | 2,86 |
| | | *Pontederia crassipes* Mart. | 0,86 |
| | | *Vigna radiata* (L.) R.Wilczek | 0,35 |
| | | *Phedimus hybridus* (L.) 't Hart | 0,092 |
| | | *Petrosedum rupestre* (L.) P.V.Heath | 0,0155 |
| | | *Sedum sexangulare* L. | 0,0084 |
| | | *Sedum album* L. | 0,0024 |
| Constructed Wetlands MFC | Adventitious | *Cyperus prolifer* Lam. | 229 |
| | | *Elodea nuttallii* (Planch.) H.St.John | 184,75 |
| | | *Phragmites australis* (Cav.) Trin. Ex Steud. | 109 |
| | | *Typha orientalis* C.Presl | 21,53 |
| | | *Typha angustifolia* L. | 18,1 |
| | | *Typha latifolia* L. | 13,4 |
| | | *Iris pseudacorus* L. | 13,27 |
| | | *Ipomoea aquatica* Forssk. | 12,42 |
| | | *Carex divisa* Huds. | 8,8 |
| | | *Juncus gerardi* Loisel. subsp. *gerardi* | 8,1 |
| | Taproot | *Wachendorfia thyrsiflora* L. | 106 |
| | | *Hyacinthus orientalis* L. | 4,86 |

than 63 %.

PMFCs performances appeared to be significantly influenced by both life forms and root architecture. Therophytes and Hemicriptophytes exhibited higher median values than other life forms, though the Geophyte group showed a very high power density value despite having a lower median. In contrast, CW-PMFCs do not seemed to be significantly affected by the botanical traits considered, likely due to the limited data collected for this type of experimental configuration.

The best performing plant species in PMFCs were found to include *Carex hirta*, *Alisma plantago-aquatica*, *Glyceria maxima* and *Canna indica*, all of which have adventitious (stoloniferous/rhizomatous) root type. *G. maxima* and *C. indica* are geophytes, while *A. plantago-aquatica* is a hydrophyte.

Consequently, epiphytes, chamaephytes and nanophanerophyte, and plants with fibrous, fasciculated or branched root types appeared to be less suitable for PMFCs, as they exhibited lower median values and are significantly different from other groups by each criterion. While Therophytes, as annual species, are not the most practical for technological applications in experimental context, Hemicryptophytes and Geophytes seemed to be recommended for PMFCs.

However, this study faced several constraints that reduced the dataset, and may have affected our results and final considerations. Nomenclature issues hindered the identification of the correct species used in PMFCs, making it difficult to replicate experiments, an essential requirement in scientific research. Additionally, the absence of a common benchmark for reporting electrical performance and the lack of unambiguous matches with each species, led to further reduction of the data pool.

Therefore, we strongly recommend to accurately indicating the scientific name (including the author of the name) of plants to ensure replicability of experimental designs, and defining a standard measure for reporting electrical performance.

The choice of species for use in PMFCs should be based not only on the traits considered in this study but also on the implications for biodiversity, especially when PMFC are used outdoors. Biodiversity is a crucial component of sustainability. If PMFCs produce clean energy but use invasive alien species in outdoor applications, their sustainability is compromised.

Our literature review identified several species of concern in this regard. For example, *Arundo donax, Ipomea aquatica, Cenchrus setaceus, Pistia stratiotes* and *Sporobolus anglicus* are considered invasive alien species in many countries outside their natural distribution range, where they negatively affect natural habitats.

*Cenchrus setaceus*, native to North Africa and the Middle East, is one of the most invasive species in Tenerife and other areas (e.g. California, Hawaii, South Africa), where it rapidly spreads along roads from urbanized to natural areas [70].

*Pistia stratiotes*, native to South America (Bolivia, Brazil, Paraguay), is considered invasive in Asia, Papua New Guinea, Canary Island, where its dense growth can impact native plant communities and aquatic organisms (macro- and micro-invertebrates, fishes) and reduce water flow in drainage and irrigation systems. This species can transform and alter trophic dynamics, resulting in long-term changes [71].

*Ipomea aquatic*, native to Southeast Asia, has been naturalized in Africa, Australia, the Pacific Islands, and North and South America. It is considered invasive in parts of its introduced range and is listed as a noxious weed in Florida and Texas in the U.S., where it spreads in human-made aquatic environments such as canals and ditches, as well as in natural lakes and along riverbanks [72].

*Arundo donax* and *Sporobolus anglicus* are among the 100 World's Worst Invasive Alien Species [73], posing a serious threat to biodiversity.

Given these considerations, we strongly recommend using native plants for PMFCs in outdoor applications. If non-native species must be considered, a risk assessment of their invasion potential, such as the method proposed by Weber and Gut [74], should be conducted.

In conclusion, the species used to construct PMFCs represent only one of the many variables that can influence their performance. However, the choice of species should consider not only their electrical performance but also their implications for biodiversity to enhance the sustainability of PMFCs.

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## Data availability statement

All data used in this paper are published, and references are cited in the article.

## CRediT authorship contribution statement

**Ilaria Brugellis:** Writing – original draft, Investigation. **Marco Grassi:** Validation, Formal analysis, Data curation. **Piero Malcovati:** Project administration, Funding acquisition. **Silvia Assini:** Writing – review & editing, Supervision, Methodology, Conceptualization.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve grammar, readability and flow of the written text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## 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.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38733.

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