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REVIEW PAPER

Use of giant reed (*Arundo donax* L.) for polymer composites obtaining: a mapping review

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Abstract The massive biomass availability generated by the common giant reed (*Arundo donax* L.) motivates the research for its possible industrial use for high-added-value products through a biorefinery approach. The literature demonstrates the potential of common cane to obtain different high-value compounds, such as levulinic acid, oligosaccharides, fermentable sugars, highly digestible fiber for animal feed, polyphenols, and natural fibers for composite materials, among others. *Arundo* can also provide valuable lignocellulosic fibers with an application as composite reinforcement, which is the aim of this review. The work is split into different sections: fiber obtaining, mainly done by mechanical procedures, fiber characterization (composition, thermal degradation, "mechanical properties", and crystallinity), and properties of composites with reed fiber. Most authors refer to producing board panels with insulating properties, followed by introducing reed fibers or ground materials in thermoset resins. Few papers focus on the production of thermoplastic composites with *Arundo*, which shows the opportunity for deepening research in this area. PRISMA flowchart has been followed to perform the literature review. Different sources have been used, and retrieved results have been combined to obtain the core studies assessed in this review, evaluating the options of using *Arundo* fibers to obtain polymer composites.

Keywords *Arundo donax* · Giant reed · Biomass · Fibers · Composites

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Introduction

Certain plant species, such as *Arundo donax* L., also known as common cane, giant reed, or reed, have spread without control in many areas of the globe. Specifically, the giant reed is among the top 100 most dangerous invasive species in the world, according to the International Union for the

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Conservation of Nature (Lowe et al. 2000), due to its rapid growth, pyrophyte nature, and contribution to the spread of fires. Of particular concern is the distribution of *Arundo* in the Mediterranean or subtropical climate areas, such as Algeria, Morocco, Brazil, France, Portugal, Spain, Italy, and Australia, among others (Jiménez-Ruiz et al. 2021). Despite its rapid growth and potential invasive character, this species is not included in Europe's list of invasive alien species of Union concern (European Union 2017).

Arundo donax L. is a perennial Grass from the *Gramineae* family. Despite its uncertain origin, due to the small size and the high number of chromosomes, many authors place it in East Asia (Jensen et al. 2018). Giant reed produces flowers, although its seeds are not usually viable, at least out of Asia (Jiménez-Ruiz et al. 2021). This plant reproduces through the rhizome or by producing roots on the nodes (Corno et al. 2014), which explains its rapid spread and poor genetic diversity (Pilu et al. 2014; Sicilia et al. 2020). Figure1 shows some specimens of *Arundo* and the main parts of the plant: leaves and culms or stems.

Culms are hollow and have 2–3 cm diameters, reaching up to 6 m in height, with stem-clasping leaves along the entire stem (Csurhes 2016). The rapid growth of this species and its quick adaption to a wide range of environmental conditions have contributed to its great spread and naturalization, especially in Mediterranean countries (Lambertini 2019; Shtein et al. 2021). This plant species provides good yields (Scordia and Cosentino 2019) even under drought or high salinity (Sánchez et al. 2015; Licursi et al. 2018; Romero-Munar et al. 2018), pointing it as a promising source of lignocellulosic feedstock.

Several studies deal with using such plants from established crops, and the EU includes the reed as a relevant energy crop (Eurostat 2020). Its high biomass production explains the vast literature about optimizing the crop for its use in biorefineries (Copani et al. 2013; Cosentino et al. 2014, 2016), especially for bioethanol production and bioenergy (Accardi et al. 2015; Jensen et al. 2018). Reed has also gained attention for obtaining some biomolecules, such as furfural or levulinic acid, among others (Raspolli Galletti et al. 2013; Antonetti et al. 2015; Di Fidio et al. 2020). Other uses of *Arundo* have been investigated, such as paper and pulp (Shatalov and Pereira 2006; Raposo Oliveira Garcez et al. 2022) or biochar production (Ahmed 2016), or an absorbent material for oil spill recovery (Fiore et al. 2019; Piperopoulos et al. 2021). Some other uses for *Arundo* are found in the restoration of traditional architecture (Malheiro et al. 2021) and as an insulation material (Barreca et al. 2019). Its cultivation is also a strategy for soil bioremediation (Alshaal et al. 2015; Fernando et al. 2016), with the additional benefit of the biomass's ulterior valorization for obtaining methane or biochar.

Compared to the extensive research on biofuels and biomolecules, little attention has been paid to obtaining reed composites. This paper aims to comprehensively review *Arundo*'s potential for its exploitation as reinforcement or filler of polymer composites, including fiber extraction procedures and fiber and derived materials characterization.

Fig. 1 **a** *Arundo donax* L. aboveground parts of the plants. **b** culms and leaves separated

Materials and methods

This literature review has assessed several papers related to *Arundo* and sustainable materials, with particular attention to polymer composites. Those studies related to the biorefinery processes for the production of green molecules have not been considered in the preparation of this manuscript. A first bibliographic search was performed using the Scopus search engine, combining the "keywords" in Table 1 plus the term "*Arundo*". The search performed using "*Arundo* OR (giant reed)" led to 1584 publications in Scopus and 1551 in Web of Science (WoS) in

Table 1 Number of papers retrieved from Scopus and WoS search

Keywords	Scopus	WoS
Composite + fiber	92	46
Polymer + composite	85	20
Composite + characterization	99	24
Polymer + characterization	174	17
Fiber + characterization	230	32
Fiber + polymer	150	21
Composite + fiber + characterization	80	21

November 2022, while combining it with the different "keywords" listed below, reduced the results, as shown below:

The data from Scopus for the above "keywords" were downloaded and combined in an Excel file. After removing duplicates (same studies appearing in the different searches), a total of 292 studies result (Excel file attached as an online resource; tab "final studies"). The next step consisted of analyzing authors' "keywords" to remove those papers that, even appearing in the literature search, were not directly related to the work topic, that is, composites production with *Arundo*. The database created is also found in the already mentioned Excel file (tabs named "author keywords" and "author keywords refined", as obtained and after the refining). Some of the studies removed from the initial list are related to soil bioremediation, genomics, biosorption processes, cultivation, and energy production, among others. Some of these are still mentioned in this manuscript to settle the framework but are not studied in detail. From the authors' "keywords" refining, a final number of 48 papers remain, with 287 "keywords". A similar process was followed with the index "keywords" (those standardized by the search engine), retrieving 851 "keywords". These last "keywords" analysis was finally discarded because most of them are very vague and include terms such as "nonhuman", "plant", or "standard", among others (tab "index keywords"). So, the retrieved documents are finally those coming from the authors' "keywords" assessment (tab "final studies refined 2" in the excel file; the blank rows from the "final studies refined" tab have been removed in this sheet to make all studies more easily accessible).

A similar process was followed with the searches in WoS. In the end, after removing the duplicates, 67 studies arose from the total 182 retrieved, which, after refining, led to 25 documents. It is interesting to note the significant differences in the documents retrieval from both sources; apparently, Scopus provides a higher number of results, and both sources need a later step of refining to remove all those studies not directly related to the scope of the literature review. After the refining processes, the results of both searches were combined, leading to the same studies already selected from Scopus.

Figure 2 shows the number of publications in the last years, with different keyword combinations (plus the term "*Arundo*", not shown in the legend for clarity). The number of yearly publications (dash-line) shows a positive trend; these series refer only to the studies finally selected for the review. The continuous line provides a clearer picture of the publications per year, as it results from all the publications retrieved from the seven categories, excluding duplicates from the different searches. The figure also shows a distribution of the main author's "keywords" in the 48 papers, finally constituting the core of this research studies. When grouping all of them by similarity, it appears evident that *Arundo* is the most repeated word, with 16%. If this term is removed, as all papers contain it either in the "keywords" or in the "title" or "abstract", and following: "mechanical properties" is the most important term, followed by fibers, composite, and characterization, with 11% each one. It should be highlighted that in the graph, mechanical characterization includes mechanical, mechanics, tensile, flexural, stiffness, etc. Similarly, "composites" includes "composite", "polymer composite", or "natural fiber composite".

It is then clear that most retrieved papers focus on composites and particleboard obtaining and their mechanical characterization. At the same time, other terms such as treatments, sustainability, or curing behavior appear only residually.

Finally, as literature searches are highly dependent on the "keywords" used in the search itself and on authors' ones, as seen in Table 1, the online tool Inciteful XYZ (Literature connector) has been used to perform a final bibliographic search. This open-source tool produces graphs with connections among different papers related to a specific field, showing the relationships between various research studies dealing with *Arundo's* use for composites. The tool also provides the most relevant papers in

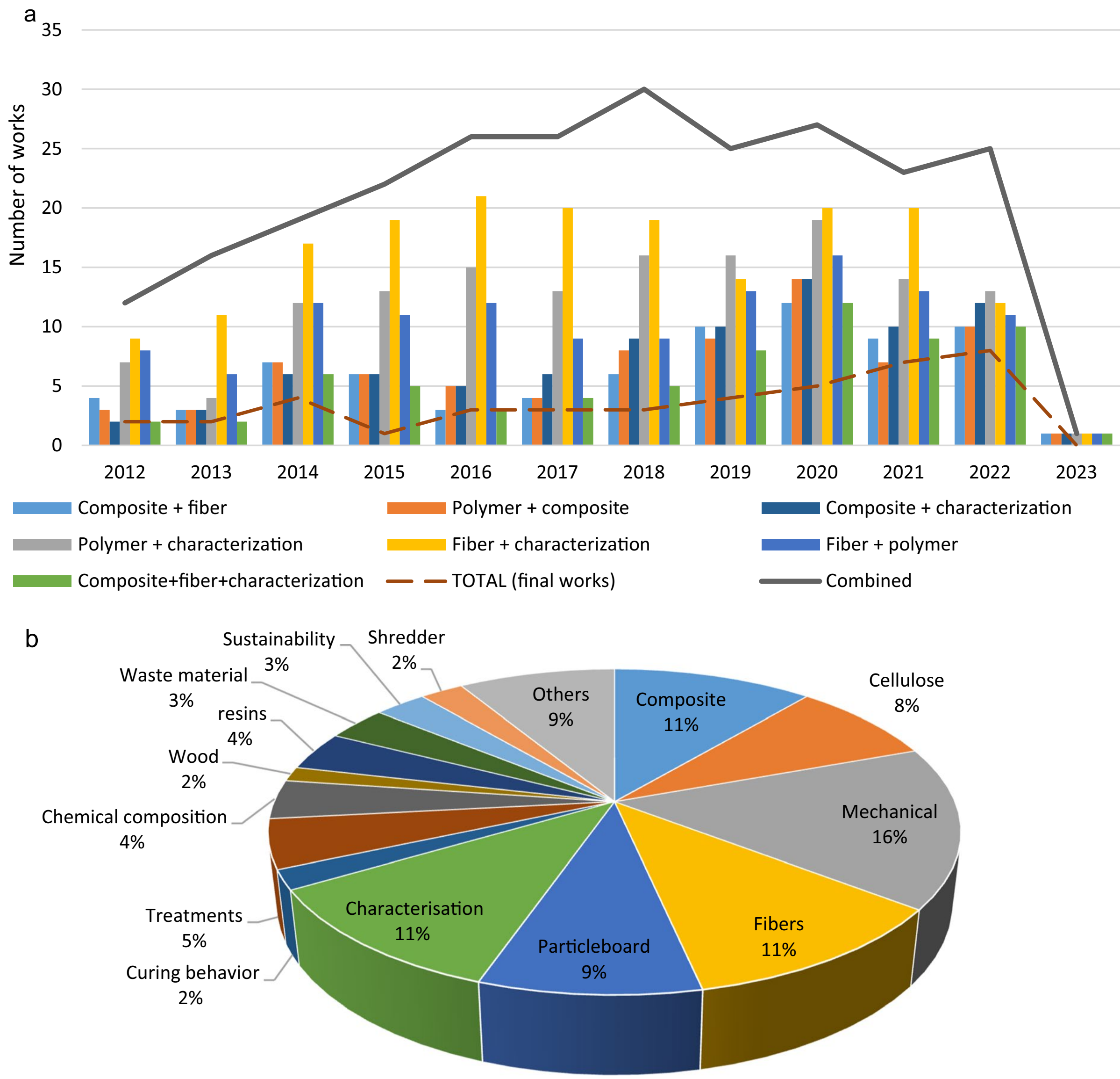

Fig. 2 **a** Evolution in the publication of papers using the words in Table 1 in the last 10 years. **b** Distribution of authors' "keywords" in the core papers of this review

the area, refining the search by the number of citations and closeness to the papers used as seeds (minimum of 5 to ensure the obtaining of relevant results), which in this case were the ones listed below:

- Characterization of a new natural fiber from *Arundo donax* L. as potential reinforcement of polymer composites:https://doi.org/10.1016/j.carbpol.2014.02.016
- Valorization of Invasive Plants from Macaronesia as Filler Materials in the Production of Natural Fiber Composites by Rotational Molding:https://doi.org/10.3390/polym13132220
- Effect of plasma treatment on the properties of *Arundo donax* L. leaf fibres and its bio-based epoxy composites: A preliminary study: https://doi.org/10.1016/J.COMPOSITESB.2016.03.053
- Characterization of raw and treated *Arundo donax L.* cellulosic fibers and their effect on the cur-

ing kinetics of bisphenol A-based benzoxazine: https://doi.org/10.1016/j.ijbiomac.2020.08.179
- Environmental Hazards of Giant Reed (*Arundo donax* L.) in the Macaronesia Region and Its Characterisation as a Potential Source for the Production of Natural Fibre Composites:https://doi.org/10.3390/polym13132101
- The manufacture of particleboards using mixture of reed (surface layer) and commercial species (middle layer):https://doi.org/10.1007/s00107-010-0437-7
- Characterization of Fibers from Culms and Leaves of *Arundo donax* L. (Poaceae) for Handmade Paper Production:https://doi.org/10.1080/15440478.2022.2076005

The software also provides a list of the most relevant papers in the field, ranging by PageRank (number of citations), similar papers (biased by publication data), and most important recent papers, combining the number of citations, field relevance, and publication date. This list was compared to that obtained from the Scopus and WoS searches. Again, not all references retrieved directly relate to the topic assessed but focus instead on other types of fibers. In any case, this is an interesting tool for the very first stages of research. After comparing the documents from this search with the ones obtained from WoS and Scopus, any new references were included. Finally, a total of 83 studies were referenced during the preparation of this manuscript. Figure 3 summarizes all the processes, following the flow chart established by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

Fibers obtained from giant reed

The methods for obtaining giant reed fibers are mechanical, chemical, or a combination of both.

Mechanical procedures are the most extended ones in the literature. Most authors process the lignocellulosic material by chopping and grinding it, using the resulting material for obtaining the composites (Fiore et al. 2014c, a; Bessa et al. 2020, 2021b). Several authors also used this approach for particleboard production (García-Ortuño et al. 2011; Ferrández-García et al. 2012; Andreu-Rodríguez et al. 2013; Ramos et al. 2018; Barreca et al. 2019; Ferrández-García et al. 2019; Ferrández Villena et al. 2020b, a; Ferrández-García et al. 2020). Other authors focused on using bast fibers obtained with a scalpel and a brush (Fiore et al. 2014a; Scalici et al. 2016). Other authors proposed using chemical methods to get cellulosic fibers with different applications. For example, Shatalov and Pereira (2013) conducted a first hydrolysis to remove hemicellulose and lignin, producing a cellulose pulp with around 94% α-cellulose. Tarchoun et al. (2019) followed a completely chlorine-free approach to get microcrystalline cellulose with up to 80% crystallinity. Barana et al. (2016) have proposed a sequential method for obtaining lignin, hemicellulose, and cellulose nanocrystals, using a chemical procedure consisting of an alkaline treatment followed by bleaching and acid hydrolysis. These authors recovered around 50% of the cellulose, hemicellulose, and lignin. Martínez-Sanz et al. (2018) have prepared lignocellulosic films by selective removal of lignin and hemicellulose by a similar chemical method. The films, especially those obtained after hemicellulose removal, showed good mechanical and water barrier properties and high transparency, comparable to those for thermoplastic starch, making them interesting for the packaging industry.

Similarly, Pinto and collaborators (2015) have proposed pulping *Arundo* stalks in an alkali solution at a moderate temperature (160 °C) to obtain cellulose pulp. The lignin from the black liquor (about 100 g lignin/kg of dry matter) was also recovered, allowing further valorization.

Finally, Suárez et al. have developed a lab-scale procedure based on a series of rolling mills to open the reed culms and separate the fibrous material from the softer one (Suárez et al. 2021, 2022b; Ortega et al. 2021). Finer fibers with higher cellulose content (about 67%) and good "mechanical properties" (Suárez et al. 2022a) can be obtained by combining chemical soaking in a NaOH solution and mechanical processing.

Fiber characterization

Table 2 summarizes the main composition and properties of *Arundo* fibers reported in the literature for composite applications. There is a considerable dispersion of data for the chemical composition from the different published studies, which can be attributed

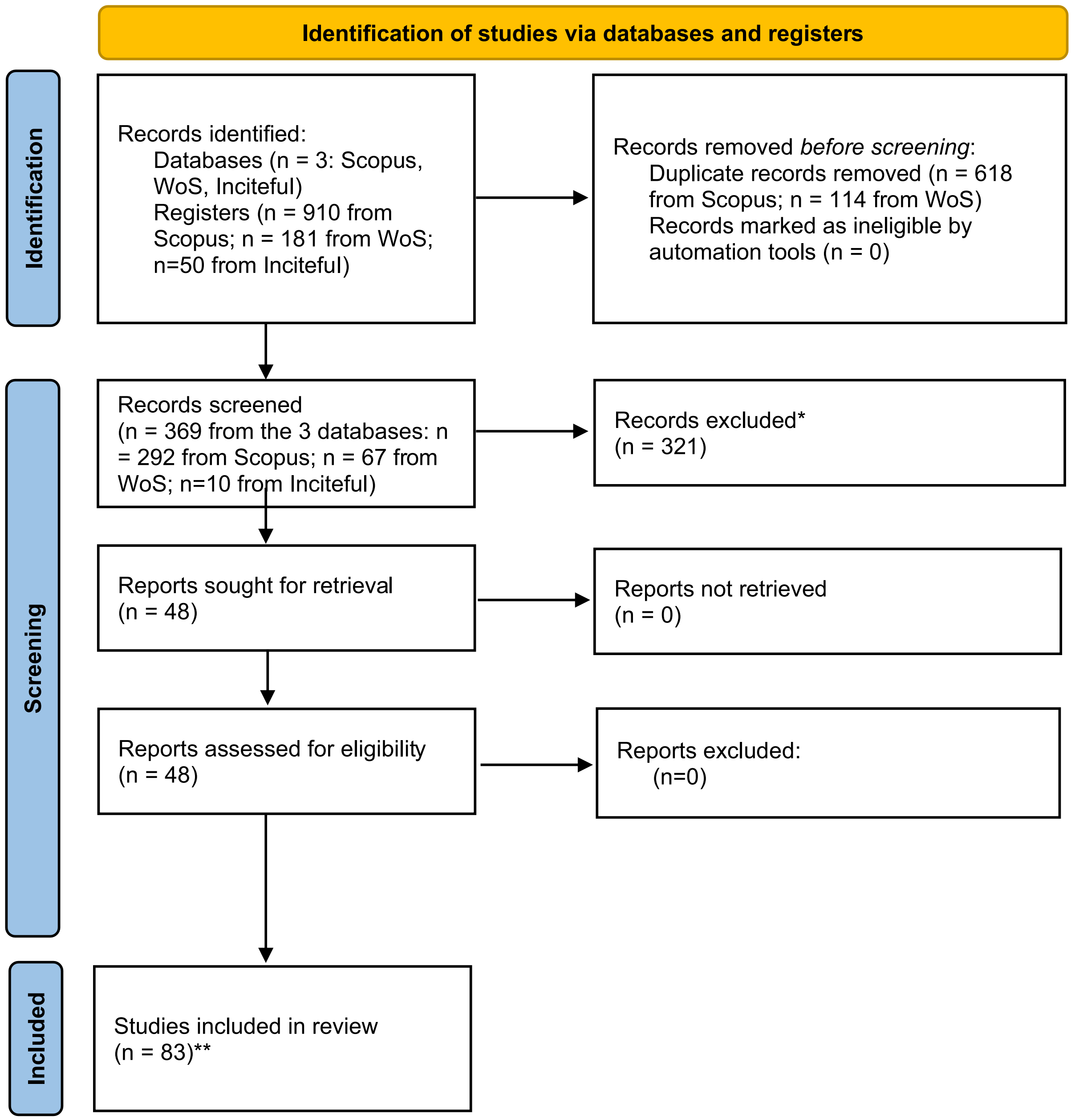

Fig. 3 Flowchart following PRISMA guidelines followed for the literature review

to the reed processing for fiber obtaining. Most studies have been performed with a mechanical procedure and show higher lignin content (17–24%) than those fibers obtained by combining a chemical and mechanical process (5.3%). Only some authors have calculated the density of the fibers, obtaining higher values for those fibers with higher cellulose content; other authors have also found a positive correlation between the cellulose content of a fiber and its density (Charca et al. 2021; Suárez et al. 2022a). Reed fibers obtained by simple mechanical procedures show about 35–45% cellulose, while those obtained by combining chemical and mechanical operations have an increased cellulose content, almost reaching 70%. Fibers commonly used in composites show a wide range of compositions, with cellulose contents

Table 2 Properties of fibers obtained from giant reed for composites application

Material	Procedure	Composition			Density (g/cm^3)	Degradation temperature^A (°C)	Tensile strength (MPa)	Elastic modulus (GPa)	Crystallinity index (%)	References
		Klason Lignin (%)	Cellulose (%)	Hemicellulose (%)						
Stems fibers	Rolling mill	24.1 ± 1.4	45.2 ± 3.0	35.1 ± 2.8	–	233.3 ± 5.7	–	–	–	Suárez et al. (2021)
	Manual decortication + scalpel	17.2	43.2	20.5	1.17 ± 0.00	115 (275)^B	248	9.4	–	Fiore et al. (2014b)
	Chemical soaking + mechanical	5.3 ± 0.1	67.5 ± 1.9	15.3 ± 4.6	1.55 ± 0.05	237.8 (273)^C	905 ± 300	45 ± 12	66.7	Suárez et al. (2022a)
	Milling	24.9 ± 0.3	38.0 ± 3.7	42.4 ± 1.3	1.17 ± 0.08	226.9 (264)^C	–	–	59.1	Suárez et al. (2022a)
	Milling	19.8	35.5	26.8	–	110 (267)^B	–	–	49.9	Bessa et al. (2020)
	Cutting	–	–	–	–	–	133.9 ± 0.3	3.5 ± 0.0	–	Manniello et al. (2022a)
Leaves fibers	Combing with a metal brush	–	–	–	–	130 (210)^B	174 ± 146	16 ± 12	–	Scalici et al. (2016)
	Chemical soaking	0.8 ± 0.1	68.8 ± 4.3	20.0 ± 3.8	1.63 ± 0.05	175.9 (280)^C	1000 ± 500	39 ± 25	73.1	Suárez et al. (2022a)

[A] Temperature for 5% weight lose

[B] Moisture (authors report onset degradation temperature placed in brackets)

[C] Moisture (10% weight loss temperature in brackets) from ≈ 40% for the wheat straw to 85% for ramie or over 70% for kenaf, flax, or hemp (Henrique et al. 2015). The literature shows a clear linear relationship between cellulose content and crystallinity index for cotton (Oh et al. 2005; Kim et al. 2018; Abidi and Manike 2018), as also happening in the few papers providing these values for *Arundo* fibers.

Thermal degradation temperatures of fibers obtained from giant reed are in the same range in the different studies, with temperatures above 230 °C, which confirms their suitability for polymer composites production, including thermoplastic and thermoset matrices. These are also in the same range as other commonly used vegetal fibers, such as flax or jute (Fiore et al. 2014b), banana, abaca (Ortega et al. 2013), or hemp (Kabir et al. 2012). The dominant mechanism occurring during the thermal degradation of biomass is diffusion-based phenomena (Ornaghi et al. 2020), mainly attributed in the first stages to cellulose and hemicellulose degradation. Their mutual ratio in the total share of the cellulose fraction, the extractive low molecular weight compounds, and the moisture in the fibers directly affect the material degradation onset temperatures. It is observed in the table that some authors reported lower degradation temperatures due to humidity evaporation, which increased if considered 10% weight loss instead of 5%.

The highest differences among the various studies are observed for the "mechanical properties" of the fibers; this is attributed, again, to the different processing of the biomass. The thick bast fibers have a less homogenous surface than the thinner ones, which can significantly influence the final values obtained (as cross-sections can also have considerable variations). From Table 2, it is observed that those fibers with higher cellulose content also provide better "mechanical properties". In particular, culm reed fibers obtained by combining chemical and mechanical procedures offered a tensile strength of 900 MPa, with an elastic modulus of 45 GPa, in the range of other lignocellulose fibers commonly used in the composites sector. For instance, kenaf fibers provided tensile strength close to 600 MPa (Wang et al. 2016), jute of about 300 MPa and 13 GPa of elastic modulus (Barreto et al. 2010), flax of about 1400 MPa and 58 GPa (Zhu et al. 2013), and bamboo 140–230 MPa and 11–17 GPa (Yu et al. 2022). Values reported in the literature for the mechanical behavior of other fibers are also highly variable (Table 3) due to the assay's sensitivity to the geometry of the single fiber (a circular section is usually assumed, although it is not always accurate) and the different testing conditions.

Table 3 summarizes some of the properties for different lignocellulose fibers to provide a clear comparison of properties. As observed, cellulose content varies from around 30% for bamboo and jute to 80% for *agave americana*, flax or sisal. *Arundo* fibers provide a cellulose content close to 70%, when extracted by the combined chemical and mechanical procedure, thus in the range of other fibers commonly used for composites obtaining, which is also observed for "mechanical properties". From this summary, the relationship between cellulose content and crystallinity index is patent. As already mentioned, there is a wide variation in such properties, which is due not only to the natural origin of the fibers, but also to their irregularities in shape and diameter. Fibers from giant reed exhibit a mechanical behavior also comparable to other lignocellulose fibers, such as jute, flax, abaca or sisal. Crystallinity index for *Arundo* fibers is close to sisal and abaca, higher than jute, banana or kenaf, although lower than flax.

The potential of *Arundo* for composite reinforcement is clear, as reported by several authors, but also when comparing the results with other widely used vegetal fibers. Lignocellulose fibers are considered, in general terms, as a sustainable alternative for composites production. However, the need of resources for their cultivation needs also to be considered; water, fertilizers and soil use together with extraction and treatment processes should be taken into account when analyzing the impact of such materials in the environment and their economic profitability. An alternative to reduce costs and environment impact is the use of vegetal residues or by-products. In this sense, various materials have been proposed in the literature, from wood dust, spent buckwheat, rice and wheat straw, or banana fibers. A different option is the use of biomass with a rapid growth and low requirements, which is the case of *Arundo donax* (Licursi et al. 2018; Scordia and Cosentino 2019). The rapid growth of this plant and its ability to proliferate even under severe droughts makes its use particularly interesting for the production of green compounds and products in the context of a biorefinery.

Arundo donax is not, for the moment, a commercial crop, although some experimental plantations have been studied, mainly in Italy. However, there is

Table 3 Summary of properties for different lignocellulose fibers

Fiber	Cellulose (%)	Density (g/cm^3)	Degradation temperature (ºC)	Tensile strength (MPa)	Elastic modulus (GPa)	Diameter (μm)	Crystallinity (%)	References
Agave americana	61–80	1.3–1.4	210–290	640–1200	2–9	100–150	–	Charca et al. (2021), Ortega et al. (2019), Hulle et al. (2015)
Arundo donax	43–68	1.2–1.6	273–275	248–905	9–45	157	66.7	Fiore et al. (2014b) Suárez et al. (2022a)
Jute	33–72	1.3–1.5	218–330	300–860	13–27	–	55–58	Barreto et al. (2010), Fiore et al. (2014b), Henrique et al. (2015), Yu et al. (2022); Zhu et al. (2013)
Flax	71–81	1.4–1.5	210–282	345–1454	28–68	10–80	86.1	Fiore et al. (2014b), Henrique et al. (2015), Ortega et al. (2013), Wang et al. (2016), Zhu et al. (2013)
Sisal	66–78	1.5	302	511–635	9–22	–	72	Barreto et al. (2010), Fiore et al. (2014b, Henrique et al. (2015), Ortega et al. (2013)
Banana	60–65	1.5	270	230–1032	34–37	180	39	Barreto et al. (2010), Henrique et al. (2015), Ortega et al. (2013)

Table 3 (continued)

Fiber	Cellulose (%)	Density (g/cm^3)	Degradation temperature (°C)	Tensile strength (MPa)	Elastic modulus (GPa)	Diameter (μm)	Crystallinity (%)	References
Abaca	56–63	1.5	273	400–700	12–24	381	69	Henrique et al. (2015), Ortega et al. (2013), Yu et al. (2022)
Kenaf	61–72	1.2	–	240–627	14–53	–	41–48	Barreto et al. (2010), Wang et al. (2016), Zhu et al. (2013)

extensive literature focusing on its use as raw material due to the high biomass production rates exhibited by this plant, even when grown on exhausted or polluted soils with low quality waters. Some studies signal this plant as with great potential to reduce the soil degradation and loss, especially in the Mediterranean basin, where an extreme danger of soil lose exists (Ferreira et al. 2022). Some authors have performed a life cycle assessment to compare the environmental performance of *Arundo*, determining a better environmental behavior than other crops such as maize-wheat or sorghum (Dragoni et al. 2015; Sallustio et al. 2022). However, no studies on the environmental performance of giant reed for fiber obtained have been found during the literature review performed. In any case, the studies analysing the potential impacts of *Arundo* cultivation conclude that positive environmental and economic results can be obtained, especially when using low-quality waters and marginal soils. Considering a biorefinery scheme for the production of valuable chemical compounds (such as levulinic or lactic acid, furfural, or polyphenols), the obtaining of fibers (with high cellulose content) would be a further step in the valorization of this lignocellulose material, which would not only come from a residue, but also from a low-impact crop.

In summary, *Arundo* fibers can be used in composites production, as their performance is similar to other conventionally and commercial used fibers, with the advantage of having a potential lower impact, if a good cultivation and planning is performed. Good management practices need to be ensured in order to contribute to the achievement of sustainable development goals (SDG) and reduce the risks associated to its potential invasive character. *Arundo* has the advantage of being highly resistant to pathogens and changing weather conditions, and is of perennial nature and distributed worlwide, which means that its production can take place through the year and is not accumulated in a particular season.

Giant reed as filler/reinforcement of composite materials

The studies about obtaining composites with giant reed are limited and mainly focus on particleboard production (García-Ortuño et al. 2011; Ferrández-García et al. 2012; Andreu-Rodríguez et al. 2013; Barreca et al. 2019; Ferrández-García et al. 2019; Ferrández Villena et al. 2020b; Ferrández-García et al. 2020). Those studies on composites production use shredded vegetal material (Fiore et al. 2014c, a; Bessa et al. 2020, 2021b), bast fibers obtained by combing with a teeth brush (Fiore et al. 2014b; Scalici et al. 2016), or rudimentary mechanical procedures (Suárez et al. 2021, 2022b; Ortega et al. 2021), as summarized in Table 2. This section shows the conditions and properties found in the literature for composites with *Arundo*-derived materials for particleboard production, thermoset, and thermoplastic composites.

Other authors have focused on using these fibers for building materials. These are not within the scope of this paper and so are only referenced here very briefly to show the potential of *Arundo* fibers for various applications. For example, Maniello et al. (2022a, 2022b) studied the influence of *Arundo* fibers aspect ratio in the mechanical behavior of concrete blocks, finding improvements in tensile strength and Young's modulus for 1% loaded blocks and a high positive correlation between fiber length and tensile modulus. Using reed in a plaster matrix also improved over 100% of the flexural strength of bricks (Martínez Gabarrón et al. 2014); flexural toughness can also be doubled with such fibers (Badagliacco et al. 2020). Similarly, Ismail and Jaeel (2014) proposed using up to 12.5% ash and giant reed fibers to replace sand in concrete mixes partially. The compressive strength increased by nearly 8% when adding 7.5% giant reed ashes and 2.5% for the same load of reed fibers. Finally, using *Arundo* fibers at 0.75% decreased the moisture susceptibility of asphalts while increasing the tensile strength ratio, obtaining an asphalt pavement that accomplishes with standards (Sargin Karahancer et al. 2016).

Particleboards obtaining

Regarding boards' production, Ghalehno et al. (2010) used ground material at 20–40% by weight in a urea–formaldehyde resin, obtaining a composite material, by compression molding, with better "mechanical properties" than the resin, although using wood fibers as core material (Table 4). Baquero Basto et al. (2018) incorporated 30–40% of ground reed fiber into a vegetable polyurethane resin, improving the rigidity and tensile strength of the resin, although with a decrease in flexural properties. Ferrández-García and collaborators (2019), on the other hand, obtained a composite material using only cane plant material and citric acid as a natural binder. The stems were ground to 2 mm, and 5–10% citric acid was added along with another 10% water; the boards were obtained by compressing the mixture at 150 ºC and 1.7 to 2.5 MPa for 7 min. The boards obtained have mechanical and thermal properties good enough to be used as insulating materials in construction. These same authors also produced a composite material using urea–formaldehyde resin as a matrix and ground reed in three different sizes,

Table 4 Particleboards produced with *Arundo* and properties (MOR: modulus of rupture; MOE: modulus of elasticity)

Material	Binder*	Conditions	Properties		References
			Density (kg/m^3)	Mechanical (N/mm^2)	
Ground rhizomes	None (water, 15%)	110 °C 2.5 MPa 7–15 min	700–900	MOR: 5–15 MOE: 700–2000	Ferrández Villena et al. (2020b)
Milled culms	Starch (5 and 10%)	110 °C 2.6 MPa 15 min	800–900	MOR: 7–16 MOE: 600–2500	Ferrández-García et al. (2012)
Milled culms	Citric acid (5 and 10%)	110 °C 2.6 MPa 7 min	600–850	MOR: 2–12 MOE: 260–2440	Ferrández-García et al. (2019)
Milled culms	Urea–formaldehyde (20%)	180 °C 3.3 MPa 15 min	460–600	MOR: 3.7–10 MOE: 970–1360	Flores et al. (2011)
Milled culms	Urea–formaldehyde (8%)	120 °C 2.6–3.5 MPa 4–6 min	628–820	MOR: 10.0–17.7 MOE: 1190–3025	García-Ortuño et al. (2011; Ferrández-García et al. 2020)
Cellulose microfibers from milled culms	Urea–formaldehyde (90–95%)	190 °C 23 MPa 7 min	642–680	MOR: 14–21 MOE: 2846–3246	Ait Benhamou et al. (2022)
Milled culms	Phenol formaldehyde (8–20%)	3; 25 MPa	–	MOE: 1200–2000; 1900–3400	Flores-Yepes et al. (2012)

*Percentages of the binder relate to the *Arundo* material obtaining good acoustic insulation results (Ferrández-García et al. 2020). These studies have found that lignocellulosic material from *Arundo* is suitable for producing medium-density boards with applications in indoor furniture and acoustic or insulating panels.

Composites with thermoset materials

Table 5 summarizes different combinations used in the literature with *Arundo* fibers. To get a clearer idea of the results obtained, the "mechanical properties" for the best formulations prepared in each work are given as the percentage of increase (or decrease) regarding the neat matrix.

Scalici and collaborators (2016) obtained composites using a biobased epoxy resin, using fibers from leaves at 2.5 and 5% with 1 and 3 cm length, by manual lay-up and compression molding at 1 kPa and 25ºC for 7 days. These authors found that plasma treatment of fibers provided a better adhesion between the fibers and the resin, due to the appearance of functional groups (C–O–C and C–OH) which, together with the changes in morphology, provided a higher anchorage between both materials.

The obtained composites showed improved flexural modulus, regardless of the fiber size, ratio, and treatment, while strength was only enhanced for samples with treated fibers. The best properties are obtained for treated 3 cm-length fibers at 5%, with an increase of 80% in flexural modulus and 38% in flexural strength. Similar results are obtained for the composites with 2.5% fiber. It then appears that plasma treatment is more significant than the ratio of fiber used. The damping factor (tan δ) decreased for plasma-treated fiber composites, and the glass transition temperature also shifted to higher values, showing improved bending between both materials. This effect was also confirmed by SEM observation of breakage sections, where no pull-out was observed.

Table 5 Composites providing the best results when using *Arundo* and thermoset and thermoplastic resins from different studies (E: elastic modulus, σ: strength)

Matrix	Fiber	Processing	Fiber length	Ratio (w/w %)	Variation (%)		References
					Tensile	Flexural	
Epoxy	Leaves fibers	Plasma treated (150 W, 120 s)	3 cm	5%	– –	E: + 80 σ: + 38	Scalici et al. (2016)
Epoxy	Ground stems	Untreated	150–300 µm	10%	E: + 40 σ:-38	E: + 15 σ:-35	Fiore et al. (2014c)
Polyester (thermoset)	Ground stems	NaOH 6% w/w, room T, 24 h, solution/fiber: 1:25 w/w	18–25 mm	≈10% (40%v/v)	E: + 22 σ: + 57	E: + 36 σ: + 45	Chikouche et al. (2015)
PLA	Ground stems	Injection molding; untreated fibers	300–500 µm[A]	20%	E: + 40 σ:-26	E: + 45 σ:-20	Fiore et al. (2014a)
PE	Fiber bundles; rolling mill	Compression molding; untreated fibers	75–500 µm[A]	40%	E: + 49 σ:-42	E: + 170 σ:0	Suárez et al. (2021)
PP	Fiber bundles; rolling mill	Compression molding; untreated fibers	75–500 µm[A]	40%	E: + 38 σ:-48	E: + 74 σ:-30	Suárez et al. (2021)
PE	Fiber bundles; rolling mill	Rotational molding; untreated ground fibers	> 250 µm[A]	20%	E:0 σ:-25	E:0 σ:-37	Ortega et al. (2021)
PE	Fiber bundles; rolling mill	Rotational molding; untreated ground fibers	3–4 mm	10%	E: + 43 σ:-17	E:0 σ:0	Suárez et al. (2022b)
PLA	Fiber bundles; rolling mill	Rotational molding; untreated ground fibers	3–4 mm	10%	E:0 σ:0	E: + 423 σ:-42	Suárez et al. (2022b)

[A]Mesh size

Fiore and collaborators (2014c) also prepared epoxy-based composites with ground *Arundo* stems at 5, 10, and 15%, separating the fractions by size: lower than 150 µm, 150–300 µm, 300–500 µm, and 0.5 to 2 mm. The bigger particles were not used for high loadings (over 10%) due to the high viscosity of the mix with the resin, making it impossible to cast. These authors found an increase in voids content when increasing the amount of lignocellulosic material; particle size also seems to have this effect, although to a lower extent (an increase in length leads to a slight rise in voids content). Tensile or flexural elastic modules are unaffected by the particle size. The tensile modulus is increased significantly for composites, with a higher rise for 10% composites, while flexural modules are similar regardless of the amount of fiber used. Similarly, tensile and flexural strength is reduced when *Arundo* particles are introduced within the epoxy resin due to the lack of compatibility between both materials; the higher the filler size, the more drastic reductions. Using over 10% of fibers leads to more significant reductions in strength, related to the appearance of voids and poor interaction between the resin and the fibers. In particular, the use of 15% filler led to porosity values close to 5% (almost double than for 10%-loaded composites), which results in a reduction of tensile modulus from the 2.95 GPa for the 10% composite to 2.82 GPa, which can be considered as no significant, although also reducing the tensile strength in more than a 30% (from the 41 MPa for 10% *Arundo* composite to 30 MPa for the 15% one). Glass transition temperature or dynamic "mechanical properties" were not observed for composites compared to the neat matrix. However, the incorporation of the reed results in a slithgly improved storage modulus in the rubbery state (over glass transition temperature, placed around 70 °C).

Chikouche et al. (2015) proposed using a simple NaOH treatment before introducing the fibers into a polyester matrix, varying the NaOH solution concentration from 2 to 8%. They prepared composites with 40% (in volume) of filler (about 10% in weight), finding improvements in tensile and flexural properties for all formulations. The treatment increases the mechanical behavior of the composites with increasing concentration of the soda solution, with a maximum at 6%; further increases result in lowering of the tensile and flexural strength of the composite, while mantaining the elastic modulus. An excess of alkali result in fiber weakening, which affects the final performance of the composite. Besides, it is important to emphasize the need of residual alkali neutralization to avoid fiber or matrix degradation.

Finally, Bessa and collaborators (2020, 2021a, 2021b) studied the influence of giant reed fibers on the properties of bisphenol A aniline-based polybenzoxazine composites, including not only composites' properties but also curing kinetics. First, different pretreatments were applied to the fibers (NaOH 5%, aminopropyl-trimethoxysilane 5%, or a combination of both, for 3 h at room temperature) and then introduced in a 25% w/w in the matrix (Bessa et al. 2020). They found a maximum decrease of 10% in activation energy for the resin curing for silane-treated fibers. In later research, these authors processed the *Arundo* ground culms to isolate the microcrystalline cellulose and also introduced it in the same matrix at different ratios: 5, 10, 15, and 20% in weight. They found that introducing such fibers increased the polymer glass transition temperature. The optimum loading was 15%, which resulted in a reduction of 10% in the activation energy for the resin curing (Bessa et al. 2021a). So, introducing lignocellulosic fibers from *Arundo* seems to positively influence the cross-linking of this bisphenol A-based resin.

Regarding the mechanical behavior of such composites, these authors also studied the influence of introducing 5, 10, and 15% fibers treated with NaOH, silane, or their combination, as in their previous work (Bessa et al. 2020). They found significant increases in glass transition temperature with increased fiber content and reduced damping factor values, especially for silanized fibers (Bessa et al. 2021b). Storage modulus increased for all composites, higher for higher loadings, and more significantly for alkali-silane-treated fibers, thus demonstrating a higher compatibility between fiber and matrix. For this treatment, glass transition temperature increased in almost 30 °C (from 188 °C for the neat resin to 217 °C), while storage modulus was increased in over 100% in the glass region, increasing from the about 2 GPa for the bisphenol-A resin to almost 3.5 GPa for the 25% silane treated fiber.

Composites with thermoplastic materials

Fiore et al. (2014a) obtained a composite material with a PLA matrix, using the ground stems as reinforcement material, at a 10 and 20% ratio, by injection molding. These authors concluded that as the reed content increased, the tensile and flexural elastic modules also increased, while the tensile and flexural strength decreased. This study found that the fiber content is more significant than the fiber length in the final properties of the composite, at least for the two fractions of ground material used (150–300 µm and 300–500 µm). Reed fibers have also been introduced in polyethylene (PE) and polypropylene (PP) matrices under compression molding (Suárez et al. 2021) in ratios of up to 40% by weight. These authors found a drastic decrease in impact properties, especially for all PP composites and for PE for 30 and 40% loadings. As observed in other studies, elastic modulus rises, and tensile strength decreases when increasing the filler ratio, although without significantly affecting flexural strength for PE. The improvements for the PP matrix are more discrete, probably due to the low processing temperature used.

Finally, the literature has also explored the rotational molding of PE and PLA with *Arundo*-derived materials. Up to 20% of fibers were introduced in PE at different particle sizes: lower than 75, 75–125, 125–250, and higher than 250 µm (Ortega et al. 2021), finding decreases in tensile strength and elastic modulus for the smaller particles. Impact strength is reduced for all composites, as otherwise expected from rotomolded samples. Only the composites with larger particle size provide a similar modulus to the used PE. The specificities of this processing method, where no pressure is applied, and the lack of compatibility between the fibers and the matrix explain the poor results obtained.

Longer fibers (3–4 mm length) at 5 and 10% loadings provided no significant differences in rotomolded PE parts (except for impact strength). In contrast, impact and flexural properties are reduced for PLA-based composites (Suárez et al. 2022b). These authors have treated the fibers with a NaOH solution 1 N (40 g/l), getting fibers with increased thermal stability without any change in the "mechanical properties" of the composites. Despite the relatively poor mechanical behavior obtained for PLA composites, incorporating *Arundo* fibers results in a higher degradation in a biodisintegration assay, observed the reduction in melting and glass transition temperature after the assay. The fibers' hydrophilic character increases the composite's moisture uptake and accelerates the PLA chains' hydrolysis.

An analysis on the properties of *Arundo*-PE based composites show that tensile strength is reduced with the increase ratio of fiber, regardless the process used (compression or rotational molding). In contrast, elastic modulus tend to increase with the amount of lignocellulose fiber (Table 6). All these studies were performed by dry blending the materials in the composite before its processing (PE powder and the *Arundo* materials). That is, no melt-blending was performed, as commonly performed for injection-molded samples, for the production of compression or rotationally molded composites. Flexural properties respond more favorably to the introduction of the fibers, with lighter or no reductions in strength and higher increases in flexural modulus, reaching more than double of the value for the neat polymer. The behavior shown by giant reed composites is similar to those obtained with other lignocellulose materials. For example, rotomolded composites with 10% of agave (López-Bañuelos et al. 2012) or 10% of abaca or banana fibers (Ortega et al. 2013) shown a flexural elastic modulus of around 600 MPa (about two times higher than for neat PE). These composites also exhibited reductions of 30–50% in tensile strength, while elastic modulus was almost folded by two. Finally, regarding impact behavior, it is well-accepted that this propertie is greatly affected by the incorporation of any foreign material, due to the particularities of rotomolding, where no pressure is applied.

The research performed to date on giant reed have not incorporated any compatibilizer for the composites preparation, and only NaOH-treatments were applied, although not particular differences were found in the behavior of the composites, despite the increase in the thermal stability of the fibers. A deeper study on the surface modification of *Arundo* fibers, the changes in the topography of fibers, and its influence in the final behavior of the composite is an interesting path to explore in future research. *Arundo* fibers provide good features, comparable to other commercial fibers, and are obtained from a plant with a promising future due to its high growth rates, low requirements and potential as biorefinery's feedstock. The lifecycle assessment (LCA) of *Arundo* crops for

Table 6 "mechanical properties" of *Arundo*-PE composites

Processing	Fiber length	Ratio (w/w %)	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m^2)	References
Rotational molding; untreated fibers	3–4 mm	0	16	380	19	620	19	Suárez et al. (2022b)
		5	13	470	18	670	15	
		10	11	490	18	800	12	
Rotational molding; 1N NaOH treated fibers	3–4 mm	0	16	380	19	620	19	
		5	13	540	18	700	15	
		10	12	500	17	740	10	
Rotational molding; untreated fibers	> 250 µm[A]	0	16	400	18	650	18	Ortega et al. (2021)
		20	12	400	13	650	8	
Compression molding; untreated fibers	75–500 µm[A]	0	16	600	19	630	16	Suárez et al. (2021)
		10	13	700	20	750	14	
		20	11	850	21	1400	12	
		30	11	850	20	1700	7	
		40	9	900	18	1700	6	
Compression molding; 1N NaOH-treated fibers	75–500 µm[A]	0	16	600	19	630	16	
		10	10	700	19	750	15	
		20	12	700	19	900	9	
		30	8	760	18	1500	6	
		40	8	800	16	1500	6	

[A]Mesh size

bioenergy production have shown a positive behavior, while the LCA of reed-composite materials have not yet been investigated, which gives further options for further investigation.

Potential new functionalities of giant reed as active composite fillers

Several research papers describe the possibility of valorization of the giant reed as a valuable source of biomass and fibers and underline the possibility of obtaining extracts and valuable chemical products. The contained extracts and low-molecular-weight volatile compounds may be a source of compounds with additional impact on the polymeric matrix when using lignocellulosic products with low processing levels, resulting in new functional properties of composites manufactured with their use. To date, the possibility of getting additional functional features of composites produced with *Arundo donax* has not yet been investigated in the literature; however, the promising results of research already carried out for the plant raw material require consideration. Wang et al. (2011) demonstrated the possibility of extracting volatile oils with allelopathic activity. The extracted allelochemicals revealed an inhibitory effect on *M. aeruginosa*, the most common toxic cyanobacterial bloom in eutrophic freshwater sources. In the case of the production of thermoplastic composites intended for outdoor exposure, the desired feature is not only the improvement of their performance but also increased resistance to weathering conditions (water absorption and resistance to UV radiation). Girotto et al. (2021) demonstrated that the leaves of *Arundo donax* contain compounds with antioxidant properties, including phenolic compounds and terpenes.

Moreover, the rhizome also includes phytochemicals with antimicrobial activity (Pansuksan et al. 2020). Considering the possibility of migration of low-molecular compounds from extracts or oils reported for other plant-based residues used as polymeric composite fillers (Barczewski et al. 2018; Van Schoors et al. 2018), one can assume that *Arundo donax* fibers could also provide antioxidant or stabilization features to the polymer matrices, increasing processing range and improving aging behavior. This is an exciting path to explore in future research on lignocellulosic-derived composites.

Conclusions

The extensive literature published on this topic shows a high interest in using giant reed for several purposes in the industrial environment. The abundant biomass generated by this plant, its fast-growing rate, and the low inputs needed for its cultivation have made several authors signal *Arundo* as a promising source of lignocellulosic biomass. Most research focuses on using this plant for a biorefinery context and producing energy or chemical products, although obtaining fibers for several uses is also proposed.

An exciting strategy to maximize the environmental and economic benefits of lignocellulosic materials used within industrial applications is the cascade process, where the different fractions of the material (simplified to cellulose, hemicellulose, and lignin) could be separated and used. One such approach involves obtaining natural fibers with high cellulose content and valorizing the remaining fractions for other purposes. Further studies are required to determine the environmental, economic, and social impacts of *Arundo* cultivation and use, as for most natural fibers. Such studies should assess the crop performance and obtain the lignocellulosic biomass from residual materials. The lifecycle analysis of such materials should include the processing for fibers production (including their treatment) and the later composite performance (durability, recyclability, or biodegradability). In this sense, it should be highlighted that *Arundo donax* L. shows high resistance to salinity, droughts, and pathogens, which makes it possible to grow it in marginal or degraded soils and with low-quality waters. The cultivation of reed in such conditions for producing fibers (and additional products derived from a biorefinery) would imply an additional environmental benefit compared to other common plants grown for fiber-obtaining purposes, where cultivable land, fertilizers, and good-quality waters are used. However, the invasive potential character of this plant species should not be disregarded, despite the potential benefits of its cultivation. Finally, this review has shown the relevance of the extraction procedure in the cellulose content and properties of the fibers and, consequently, in composites. *Arundo*-derived materials, especially fibers, have increased tensile and flexural modules, both in thermoset and thermoplastic matrixes. Several authors have identified the need to treat the fibers, either with plasma or with chemicals, to improve the adhesion between the fiber and the matrix, reduce the number of voids and increase the "mechanical properties" (or at least not to reduce them). This work has allowed identifying the gap existing for *Arundo* fibers use in composites in the literature compared to other lignocellulosic fibers. Ground reed has been successfully used to obtain panels by compression molding and thermoset resins, while its use in thermoplastic matrices is still pretty unexplored in the literature. Besides, the antioxidant features provided by such natural materials should also be assessed in the future to improve plastic products' behavior under atmospheric conditions (UV light and humidity). Thus, there is a promising field of study framed on the green deal strategy of the EU and sustainable development goals to optimize not only the technical performance of the composites but also their environmental, economic, and social performances.

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Declarations

Conflict of interest The authors declare no potential conflict of interest.

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