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Arundo donax L. in Egypt: a potentially valuable economic plant

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ABSTRACT

Arundo donax L. (Giant reed) is a highly productive tall perennial cane usually growing in damp soil in temperate and subtropical areas of both hemispheres. The plant has an economical value for humans since ancient times. A. donax possesses high adaptability and tolerance to various environmental stresses. The plant has been reported to reproduce mainly vegetatively, as seeds are believed to be unviable. Populations usually grow near soils with an abundance of moisture. Recently, the plant started to draw attention as a promising source of biofuel due to its high growth rate and biomass production. It is also associated with various ecosystem services such as phytoremediation, cleaning water sources from pollutants and carbon sequestration. This enables the usage of the plant for habitat restoration and mitigation of climate change. The plant also has various industrial, pharmacological and medical applications. In this manuscript, we aim to discuss the origin, distribution and behavior of giant reed focusing on its presence in Egypt and the Mediterranean region. The plant is usually abolished due to its ferocious efficiency and invasive behavior. Instead, we suggest harnessing the high potential of the plant to accomplish far considerable benefits on both economic and environmental levels. This work highlights the required futuristic scientific research endeavors about giant reed especially regarding a better understanding of some debatable issues as its propagation, spread, invasiveness and potential impact on economy and ecosystems.

1. Introduction

Arundo donax L. is a perennial plant belonging to the family Poaceae (Gramineae)- subfamily Arundinoideae. Its

native range is from Western and Central Asia to temperate Eastern Asia and has been introduced into subtropical areas of the world (Ngernsaengsaruay *et al.*, 2023). It usually grows up to 4-6 meters in height (Cavallaro *et al.*, 2019; Pilu

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et al., 2013; Speck, 2003). It has a large fibrous rhizomatous root capable of diving deep into the soil to reach the dampened layers of the soil (Jiménez-Ruiz *et al.*, 2021; Mirza *et al.*, 2010; Stover *et al.*, 2018). It usually grows near river banks and creeks. It prefers humid soil but can still successfully thrive on poor soil as roadsides (Günes & Saygın, 1996).

Since ancient times, giant reeds have been used for creating numerous human tools and materials such as flutes (Boulos & Fahmy, 2007; Üner & Bayrak, 2018), paper (Caparrós *et al.*, 2007; C. M. J. Williams *et al.*, 2009), baskets, treillages and fencing for gardens, crude shelters, henhouses, farm animals fodder, pulps for teeth, fish catching tools, arrows, controlling erosions and as a plant for horticulture and aesthetical ornamentations (Antal, 2018). In folk medicine, humans have been using the rhizome of the plant due to its pharmaceutical value (Al-Snafi, 2015; Kumar *et al.*, 2021).

One major point of controversy is the the debatable connection between the widely believed seeedles vegetative propagation of the plant and its ability to spread quickly across vast regions in relatively short whiles. *A. donax* is prevalent in various regions of the world and across geographically unconnected inhabitable areas of Egypt as oases (Kassem, 2023). One could argue that seedless reproduction is not enough to interpret the ability of populations to swiftly invade new habitats. Despite the previous efforts to fathom this issue through genetic studies (Ahmad *et al.*, 2008; Guarino *et al.*, 2019) and developmental dynamics of *A. donax* seeds (Nikhade & Makde, 2014), we believe there is still much room for further research to fully understand the reproductive behavior of giant reed.

Despite behaving as a ferocious invasive species (Bruno et al., 2019; Hardesty-Moore et al., 2020; Jiménez-Ruiz et al., 2021), A. donax has been involved in several environmental applications and ecosystem services. The plant is capable of performing influential ecological benefits as bioremediation and restoration of soil quality (Alshaal et al., 2013; Jámbor & Török, 2019; Lewandowski et al., 2003; Zecca et al., 2020; Zhang et al., 2021). Further on, the giant reed is praised for its great capacity to remove pollutants and agrochemical waste from nearby water sources (Basso & Cukierman, 2005; Danelli et al., 2021; Fiorentino et al., 2017). Recently, giant reed has grown a good reputation as a promising second-generation source of biomass for bioenergy production (Cappelli et al., 2021; Corno et al., 2014; Danelli et al., 2020; Lemons e Silva et al., 2015). This privileges the plant to act as one of the hopes toward improving Earth's health and minimizing the impacts expected from global warming caused by over-dependence on conventional sources of fossil fuel.

We thus suggest that further scientific research is much needed to better control the invasive and reproductive behavior of *A. donax* especially in cultivation systems. This is clearly essential to ensure a harmonious exploitation of the environemental and economic benefits of the plant while avoiding its possible negative impact on biodiversity due to its fierce tendency to spread and remarkable outcompeting tolerence.

2. Materials and Methods

This review highlights the several promising aspects of A. donax. Such understanding is necessary to pave the way toward creating organized strategies for harnessing the huge potential of the plant. This can be attained by efficient transmutation of the once commonly considered undesired wild invasive species into a tally of remarkable economic profits and several environmental benefits. In this review, previous related scientific reseach investigations were discussed, compared and analyzed with a focus on outcomes published in the last two decades to paint a clear picture as for an efficient futuristic exploitation of giant reed's huge value. This work, thus, sheds light on the research gaps that are yet to be covered concerning A. donax. This includes: better clarification of plant's evolutionary origin, predicting the futuristic spread of the plant across the globe, the dispute regarding the methods of propagation, the mixed impact of the plant on climate change, the debatable impact of the plant on the environment, comparing the economic efficiency of the plant as a source of green energy against correspondent renewable energy sources, in addition to acquiring better scientific assets to control the ferocious invasiveness of the plant during its cultivation for biomass production.

2.1. Morphology and differentiation from closely related species

Arundo donax has various morphological advantages crowning it as a highly rated promising source for biomass. A good evidence for that, is the fact that the plant is regarded as one of the biggest plants of the genus Arundo, such a group that attains a high growth rate (Galal & Shehata, 2016; Tho et al., 2017). Rhizomes usually dive deeply for over a meter under the soil in search of humid layers (Jiménez-Ruiz et al., 2021; Stover et al., 2018). Mirza et al. (2010) reported that the plant can reach a height of eight meters and as deep as five meters in the soil under optimum conditions. The plant possesses long rhizomatous roots. These rhizomes spread in a horizontal direction and create vast dense structures. Regarding the stem (culm), it is hollow, bamboo-like with glossy internodes (Kumar et al., 2021). Leaves are distichous, glabrous with large blades 10-50 cm long, 5-70 mm wide, linear-lanceolate, flat, drooping,

cartilaginous, hairy on basal third, margins smooth, bases rounded or cordate, apex attenuate, ligules ciliolatemembrane, c. 2 mm long. The inflorescence is a panicle-like terminal, 30-60 mm long. Spikelets are 8-15 mm long, cuneate, and laterally compressed. Spikelets consisting of bracts distichously arranged along a slender axis (rhachilla), each spikelet with 2 lower more or less equal bracts (glumes), persistent, lanceolate; the succeeding bract (lemma) enclosing a flower and opposed by a hyaline scale (palea); the whole (lemma, palea and flower) termed a floret. Each pikelet comprises 2–7 fertile florets; lemma lanceolate, 6-12 mm long; membranous, 5-9 -veined, surface villous, awnless or with short awn, c. 1 mm long. Fruit is mostly a caryopsis with thin pericarp adnate to the seed (Clayton, 2002; Ngernsaengsaruay et al., 2023). Plant parts are illustrated in figure 1. Florets and inflorescence are shown in figure 2.

Arundo donax has had myriads of appellations all over the world. Some of these are common to be used as a reference to another closely related grass: Phragmites australis. In English-tongue countries the plant is generally named bamboo reed, donax cane, Spanish reed, Italian reed, Danubian reed, giant reed, or Provence cane, in addition to some generally common dubs as cane, bamboo and reed (Michela et al., 2021). The wide spread names in various nations are simply the translation of the mere word "common reed" or "cane". In Egypt, giant reed is usually known as: Kasab, Ghab, and Boos, Ghab Farsi, Ghab Baladi (Boulos, 2005). Greece: Kalamos; India: Narkul, Gaba-nal, Bara-nal,; Burma: Alokyu; France and French-speaking African countries: Canne, Canne de Provence, Roseaux; Spain as well as Latin tongue nations: Canna de Castilla, Cane Comun; Germany: Pfahlrohr, Pfeilrohr, Riesenschilf. In the Italian peninsula giant reed is referred to as: Canna, Canna montana, Calami, Donaci, Caneviera, Canna berganega, Canna di eannitu (Sicilia), Canna domestiea, Canna da roechi, Canna di stenniri, Virtamu, Ciane gergane, Canna commune, Gutamu. Furthermore, the form of the plant with variegate-shaped leaves in Italy is also dubbed using the epithet of canna zagariddara (Kassem, 2023).

A controversial issue that faces botanists is the similarity betweern giant reed and common reed. Both giant reed (*A. donax*) and common reed (*P. australis*) are very successful worldwide grasses with several morphological similarities (Pompeiano *et al.*, 2019). However, there are various ways to help researchers distinguish between these closely related cane species. These include: the lemma being pilose, glumes longer than the florets in *A. donax* while the lemmas are glabrous with hairy rachilla and glumes shorter than florets in *P. australis* (Peterson *et al.*, 2020).

We suggest that the presence of the inflorescence during flowering season can be a good asset for researchers interested in sampling the plant. The distinguishable erect shape of inflorescence facilitates recognition of the plant from closely related grasses as *P. australis* (Kassem, 2023). Other differentiating features include shoot size, leaf shape, inflorescence shape and thickness (Ngernsaengsaruay et al., 2023). However, confusion is still common, especially with the fact that both plants usually share the same habitats (Tshapa et al., 2021). Spectro-radiometry has also been used to distinguish between the two species depending on the unique wave lengths of spectral separability for each species (Fernandes et al., 2013). Others suggested the anatomy of rhizomes as a base of recognition between different reed species. In Arundo species, it is characterized by solidified unhallowed pachymorph rhizomes while *Phragmites* species rhizome can be distinguished by its aerenchyma or specialized tissue for storing air (Danin & Naenny, 2008).



Fig. 1: Different parts of Arun



Fig. 2: Unclear florets and the inflorescence of Arundo donax.

2.2. Origin, habitat and distribution

The origin of A. donax is debatable (Danelli et al., 2020). It has been suggested that giant reeds originated from Mediterranean wild plants (Mariani et al., 2010). While other tracing explorations argued that the plant originated from Eastern Asia fresh waters before diffusing all over Asia and North Africa and became naturalized in the Mediterranean regions (Hardion et al., 2014). Genetic markers have been used to trail the evolutionary origin of A. donax. It suggests that giant reed originally emerged in Asia before spreading into the basin of the Mediterranean (Ahmad et al., 2008). Zecca et al. (2020) indicated the presence of 6 lineages of A. donax spreading out from the Asian continent toward the Mediterranean Sea landscape. They traced the presumed ancient origin of the plant to be located in the southern and western edges of the Qinghai-Tibet Plateau in the Himalayas.

Hardion *et al.* (2014) investigated the origin of giant reed using plastid DNA sequencing and morpho-metric analysis on multiple samples gathered through multiple regions in the subtropics of Europe and Asia. Through ecological niche modeling, they suggested that the southern areas of the Caspian Sea, south of Iran as well as the Indus Valley are the most likely centers of origin from which the vast invasion of *A. donax* emerged. According to this hypothesis, giant reed originally spread out of Middle Eastern regions toward the west, resulting in its invasive spreading out across the basin of the Mediterranean.

Information resulting from studies regarding the ancestral history of giant reeds, can be of much value in helping in the management of plant's invasive behavior in addition to providing major assist during making plans of phytoremediation and biodiversity conservation (Zecca *et al.*, 2020).

Although it has been introduced into the Mediterranean and South Africa, the species appears to be absent from central Africa. The species has also been introduced into Australia, the southern United States to Central and South America (Ahmad et al., 2008). The plant was introduced from Mediterranean areas to North America starting from Southwest areas such as California to maintain erosion under control (Jiménez-Ruiz et al., 2021; Visconti et al., 2020). For many years, growers also used to plant giant reeds across many warm locations in the United States for the purpose of ornamentation (Antal, 2018). In California, A. donax managed to escape human cultivation and started to grow in humid areas, such as streams, narrow canals, and seepy sites in barren and beside mountains (Robbins, 1951). The plant can tolerate a vast diversity of environmental circumstances. A. donax can also thrive in all soil profiles, from dense clay to sand and gravel soil types (Fagnano et al., 2015).

Giant reed grows most successfully in well-drained soil sites where an abundance of water is provided. It can also tolerate excessive salinity. Lack of moisture may seriously affect the growth of the plant (Sánchez *et al.*, 2016) during the principal period of growth. However, droughts cause no massive harm to the plant as it surpasses the age of two or three years. The plant can naturally handle long and severe drought intervals (Romero-Munar *et al.*, 2018). It's also tolerable in times of over-indulgent humidity (Tshapa *et al.*, 2021).

In Egypt, A. donax usually dwells in swampy places of deserts and the River Nile region (Kassem, 2023; Kassem *et al.*, 2024; Zahran & El-Amier, 2014). The plant usually exists near water sources whether fresh or brackish. It prefers marginal areas near farms, agricultural drainage systems as well as estuaries, especially areas with high nutrition and organic matter content as agricultural areas, fords, and rural sewage systems (Kassem, 2023). Plant populations have scattered presence along canals, roadsides, railways and wastelands in Delta, Nile region, Mediterranean coast, Suez Canal region, Sinai, Fayum and Siwa Oasis (Cope, 2005; Kassem *et al.*, 2024). This is illustrated in figure 3. Arundo donax populations in various environments in Egypt are shown in figures 4 - 9.

Arundo donax usually grows in marginal lands alongside other related grasses as *P. australis* (Tshapa *et al.*, 2021). However, it was reported that *Phragmites australis* has a more densely prevalent existence across Egypt compared to *A. donax* and has more availability even in more barren regions (Kassem, 2023). This can be another asset for researchers to help in the differentiation of the two species as giant reed doesn't seem to ever exist far from abundant water sources. This is incontrary to *P. australis* which may well thrive even in semi-arid conditions.

The disputable question about the evolutionary origin of A. donax and its modes of dispersal across the globe confirms the need for further scientific research to better realize the invasive behavior of the plant. Population genetics is one branch that can clarify this issue by comparing the genetic composition of different populations. Therefore, creating dendrographic schemes of relationships between populaions. It can hence be easier to shed light on the evolutionary past and modes of dispersal. Thus, enabling researchers to predict the futuristic patterns of spread around the world. Genetic markers are a useful tool to pursue such suggested studies in the future. Armored with such knowledge scientists can better describe and expect the spreading patterns of the plant paving the way for harnessing its ferocious invasiveness into a beneficial outcome in the mould of several valuable ecosystem goods and services.



Fig. 3: Distribution of *A. donax* in Egypt. Green dots represent locations of confirmed availability of plant populations. The plant naturally grows in the Nile delta and valley, Suez Canal region, Sinai, north coast from Port-Said to Alexandria in addition to Western Oases as Fayum and Siwa.



Fig. 4: Arundo donax at a highway in Suez Canal region



Fig. 5: *Arundo donax* at a brackish lake near the Mediterranean Sea.



Fig. 6: Arundo donax at adjacent to Ford from the Nile.



Fig. 7: Arundo donax in a farm area within Nile Delta.



Fig. 8: Arundo donax at a brackish estuary in Suez Canal Region.



Fig. 9: Arundo donax in Siwa Oasis.

2.3. Arundo donax and climate change

Arundo donax can successfully contribute to achieving various goals of sustainable development set by the United Nations. The plant is involved in sustainability aims of food security, sustainable farming and renewable bioenergy. Studies have revealed the ability of giant reeds to improve farm areas under the impact of climate change in terms of land resilience and agricultural productivity (Bonfante *et al.*, 2017) in addition to decreasing environmental impacts (D'Imporzano *et al.*, 2018). Providing its bioremediation power, the plant represents a key natural solution in mitigating the impacts of climate change by improving soil fertility and restoring habitats (Jámbor & Török, 2019; Zhang *et al.*, 2021). As with any bioenergy crop, *A. donax*

possesses the advantage of carbon neutrality. This is due to the fact that biomass, used as a source of biofuel, transmits the same amount of carbon emissions to the atmosphere which it has equally absorbed from the air during photosynthesis. Thus, a bioenergy system doesn't increase atmospheric carbon emissions any further. This is a clear advantage that is missed in traditional fossil fuels. Carbon neutrality, or the state of net-zero CO₂ emissions, can be applied in the context of CO₂-releasing processes such as: energy production, transportation, agriculture and industry (European Parliament, 2019).

The Bioenergy potential of *A. donax* enables it to be used as a cheap effective alternative to conventional fossil fuel sources. The plant thus can help to reduce emissions of greenhouse gas while increasing the stock of soil carbon (Bonfante *et al.*, 2017; Fagnano *et al.*, 2015). Combined with its high carbon sequestration capacity (Kassem *et al.*, 2024), the plant is a bargain for mitigating climate change induced by the excessive usage of fossil fuels.

Despite the general positive role of the plant to enhance a clean Earth atmosphere, some research investigations argued that bioenergy production from *A. donax* alongside other crops may result in a mixed impact on air quality (Porter, Rosenstiel, *et al.*, 2012). Others reported that the plant is involved in thermal emissions affecting the climate (Jeguirim *et al.*, 2010). Mass cultivation of these biofuel plants is accused of generating organic volatile compounds as isoprene (Maxfield, 2000). Thus, it can relate to higher levels of unfavorable atmospheric gases as ozone and aerosol (Porter, Barsanti, *et al.*, 2012).

Due to these mixed opinions about the impact of *A. donax* on the serious issue of climate change, it is suggested that more scientific investigation is required to clarify the exact impact of mass cultivation of giant reed on the global phenomenon of climate change. If the plant is proven to display an overall positive effect in mitigating global warming, the plant would then be a huge assist to grant the planet with the climatic and environmental rehabilitation it deeply needs.

Climate change can by its turn affect the normal behavior, productivity and geographical range of giant reed. Physiological patterns of the plant can be hugely affected by surrounding variations in climatic conditions. According to a study performed in the xeric dry areas of the Mediterranean, a collapse in water regimes due to climate change can result in a decrease of 65% in giant reed yield productivity (Curt *et al.*, 2018). Temperature has a major role in controlling the physiological development of the plant (Cosentino *et al.*, 2006). Flowering time may also be subject to changes in climatic conditions caused by different

latitudes (Cantaluppi *et al.*, 2016). In light of this phenomenon, global warming resulting from climate change is expected to shift both the chronological behavior (as the timing of flowering) and distribution range of giant reed populations which naturally prefer temperate Mediterranean climates and subtropical regions (Da Costa *et al.*, 2021; Jiménez-Ruiz *et al.*, 2021).

One of the major impacts of climate change is the continuous increase of salinity in the Mediterranean basin (Di Mola *et al.*, 2018). Though *A. donax* has high adaptability to salinity (De Stefano *et al.*, 2018; Kassem *et al.*, 2024; Sánchez *et al.*, 2016), a matter of concern is whether the plant can deal with such unusual salt stress. Di Mola *et al.* (2018) indicated remarkable tolerance by cultivated giant reed against unnatural salinity caused by the impact of climate change in the Mediterranean region. The plant was found to possess stable water use efficiency and to produce normal biomass yield with high thresholds of salinity tolerance.

2.4. Invasive behavior

Arundo donax is considered one of the most aggressive invasive species globally (Hardion *et al.*, 2014; Jiménez-Ruiz *et al.*, 2021) especially when existing out of its natural range (Zecca *et al.*, 2020). This is one of the biggest controversies against cultivating the plant for biomass production. This can be made clear by the fact that a small number of individuals may quickly and wildly invade stream banks as well as road-sides. As the plant establishes itself, it shows a powerful capability to vigorously compete and fully inhibit the surrounding native plant community. As giant reed reproduces via vegetative methods, it can establish pure stands, usually at the cost of the native vegetation (Wells *et al.*, 1980). Understanding the spreading behavior and geographical origin of invasive species can help control their presence (Lafuma *et al.*, 2003).

Remarkably, the invasiveness of *A. donax* may also change the behavior of native fauna. A study that used remote cameras, managed to detect those mammals and carnivore were deterred away from habitats occupied by the invasive plant. This outcome suggests that native animals have a preference against giant reed habitats which may potentially represent a refuge for predators (Hardesty-Moore *et al.*, 2020). The aggressive ability of giant reeds to replace correspondent native grasses can lead to a weakened stability of banks which were naturally maintained by the original local vegetation (Stover *et al.*, 2018).

The invasive behavior of giant reed alongside other grasses such as *P. australis* usually leads local inhabitants in the Egyptian countryside to clean it by cutting off and by fire (Kassem, 2023). In several locations as the Egyptian city of

Fayum, local farmers usually remove *A. donax* populations to expand the agricultural areas as well as to use the plant culms for creating fences around houses. Removal usually takes place by cutting off (Kassem, 2023). Another common way in Egypt to remove *A. donax* and other large grasses is by burning (Kassem *et al.*, 2024). Areas near Mediterranean lakes in Egypt such as Mariout and Manzala lakes almost lack any remarkable presence of *A. donax* populations. This is due to the governmental endeavor to clean Egyptian lakes of pollution and encroachments through a large effort of a sustainable development scheme (Egypt's projects map, 2022). However, Coffman *et al.* (2010) suggest that wildfires can promote the dominance of giant reeds. The plant can resprout rapidly afterward and grow 3-4 times faster than any woody riparian plant (Coffman *et al.*, 2010).

Biological control or management by biological enemies can also be considered in mitigating the rapid invasive spread of A. donax. This is due to its negative impact on native biodiversity in addition to its fresh water consumption which may potentially affect water share used in farming and various human civil purposes (Tarin et al., 2013). A major method to restore natural habitats after a giant reed invasion is the direct removal of the plant and replacing it with plantations of native species (Bruno et al., 2019). Biological resistance is another effective method against the invasive behavior of A. donax. Kirk et al. (2003) suggested that the presence of various groups of insects (such as orders: Diptera and Hymenoptera) can cause mortality of the plant in infested areas. They cited a positive impact of fungal pathogens as well (Kirk et al., 2003). Spencer et al. (2008) used glyphosate to mitigate the invasive behavior of the plant. They conducted the method of foliar spray and they reported its effectiveness in killing giant reed plants (Spencer et al., 2008). On the other hand, major threats to A. donax include the various negative impacts resulting from climate change as: high salinity (Di Mola et al., 2018), global warming, rising sea levels and unusual drought (Elahinejad et al., 2023).

Having clarified the wild spreading behavior of *A. donax*, one could argue that its invasiveness is a major concern for any plans regarding its mass cultivation. Despite the ability of the plant to perform environmental benefits as phytoremediation (Fagnano *et al.*, 2015; Zucaro *et al.*, 2015), the plant, on the other hand, can dramatically change the equilibrium of habitats when introduced due to its wild invasive tendency (Jiménez-Ruiz *et al.*, 2021; Zecca *et al.*, 2020). More scientific knowledge is required through further research with the aim of revealing any unpredictable uncontrolled dispersion of the breaded cultivates of giant reed. This includes identification of all factors that may enhance or hamper the sudden spread of cultivated reeds as

well as the required practical measurements that can ensure strict control over the vegetative propagation of the individuals within and around cultivation areas.

2.5. Tolerance and genetic adaptability of Arundo donax

The plant is very advantageous for cropping as it can successfully tolerate various stress factors and hard surrounding conditions as salt stress (De Stefano et al., 2018; Di Mola et al., 2018; Kassem et al., 2024; Sánchez et al., 2016), heat, low temperature and drought (Lino et al., 2023). The plant manages to adapt well to water-logging stress (Tshapa et al., 2021). However, environmental conditions can still affect the functional traits of the thriving plant and impact its quality and potential as a source of bioenergy (Cocozza et al., 2020; Kassem et al., 2024). Giant reed in Egyptian habitats was reported to perform a considerable morphological plasticity to successfully cope with heterogeneous environments (Galal & Shehata, 2016). The adaptability and efficient stress resistance of A. donax enable its cultivation for biomass even under the impacts of climate change (Di Mola et al., 2018).

Water stress is regarded as the most negatively influential condition against the viability of giant reeds (Sánchez *et al.*, 2016). However, other studies acclaim the remarkable capacity of giant reeds to adapt and thrive in conditions of drought. This adaptive ability is due to the high plasticity of leaves, osmotic adjustments and regulations of stomata (Romero-Munar *et al.*, 2018). The negative impact caused by water stress can also be alleviated by holding the growth of leaves and photosynthetic capacity later on through the growing season (Haworth *et al.*, 2019). Overall, the giant reed's phenotypic adaptability to drought can be attributed to its ability to display water use conservation and higher sensitivity to accumulate biomass (Faralli *et al.*, 2021).

Genetic research tools, as genetic markers, can be a huge asset to explain the origin of various morphological and behavioral tendencies of giant reed. Mariani et al. (2010) declared that the populations of A. donax may exhibit limited genetic diversity due to their dependence on vegetative reproduction. AFLP fingerprinting scored the lowest genetic diversity of giant reed among 16 accessions in the Mediterranean region with a Nei's diversity index of 0.008 (Hardion et al., 2012). On the other hand, another study suggests a higher genetic diversity in Australian populations growing near river systems with 31 different genotypes represented by 58 samples (Haddadchi et al., 2013). The dependence of the plant on vegetative methods to reproduce can interpret the relatively narrow range of genetic variation between ecotypes (Valli et al., 2017). MSAP marker and AFLP demonstrate that the remarkable ability of A. donax to spread densely while adapting through a wide range of environmental conditions can be attributed to its epigenetic diversity. The capability of *A. donax* to display various DNA methylation arrangements is essential for its success and wide invasive spread (Guarino *et al.*, 2019).

Regarding the chromosome number of A. donax, studies have been contradictory (Danelli et al., 2020). A plant's chromosome number is often reported to be between 108 and 110 (Bucci et al., 2013; Christopher & Abraham, 1971; Hardion et al., 2011; Hunter, 1934; Pizzolongo, 1962). Sánchez et al. (2021) indicated a vast variation in chromosomes tally for clones characterized in the Mediterranean. They reported a number of 98 to 122 chromosomes for studied Mediterranean breeds (Sánchez et al., 2021). Haddachi et al. (2013) suggested a number of 84 chromosomes. Studies on A. donax populations growing in the Mediterranean coast of Spain, the Rio Grande basin, Texas (USA) and Mexico have proven relatively high genetic diversity Nei's genetic diversity index of 0.243 in north-central America and 0.929 in Spain (Tarin et al., 2013).

The adaptability of *A. donax* to stressful conditions can be traced to the genetic levels. A study including RNAseq of leaf transcriptome indicated the ability of the plant to pursue transcriptional responses and regulations when faced with salt stress conditions (Sicilia *et al.*, 2020). The plant can organize gene expression to successfully thrive under soil metal stress (Shaheen *et al.*, 2018). Cultivated giant reed can be subjected to genetic improvements to increase its quality and productivity. This includes methods such as genome editing and clonal selection (Danelli *et al.*, 2020).

Due to the high value and reservoir of applications provided by A. donax, genetic improvement has been an aspiration to generate breeds with higher quality and productivity. Sánchez et al. (2021) applied the characterization of giant reed clones from the Mediterranean landscape. Under a greenhouse environment, their clones proved no clear correlation between the physiological attributes of the plant and the genetic structure despite the large difference in chromosome count. Evangelistella et al. (2017) used RNA sequencing (RNA-seq) and characterization of transcriptome extracted from A. donax leaves to develop a higher-quality yield for biofuel production. They used BLAST characterization to identify specific important genes that are responsible for essential metabolic processes related to higher bioenergy efficiency as the synthesis of cellulose and lignin as well as fixation of carbon. Their outcome proposes that simple sequence repeats (SSR) appeared more abundantly in intergenic areas compared to coding DNA areas (Evangelistella et al., 2017).

Valli *et al.* (2017) reported that physical mutagenesis using γ -irradiation can be an influential tool in creating various phenotypes with several morphological alterations that may serve in using giant reeds with higher efficiency in agriculture and industry. We believe a further investigation on this research point would be fruitful in improving the quality of the yield within cultivation systems.

2.6 Ecosystem services and goods

A huge advantage displayed by A. donax is its ability to provide several valuable environmental benefits while being cultivated for other economic purposes. The plant has the ability to successfully uptake trace metals (Danelli et al., 2021) and decrease the salinity and pH of toxic red mud (Zhang et al., 2021). Populations can display a noticeably high capacity to clean nearby water bodies from agrochemical waste and residuals (Basso & Cukierman, 2005). The plant can cleanse polluted water from organic pollutants as well as heavy metal elements including: Pb, Zn, Cu, Ni, Co and Cr (Brown et al., 1994; Brooks, 1994; and Lombi et al., 2001). Galal & Shehata (2016) reported the prominent capacity of A. donax in Egyptian habitats to amass metals. Heavy metals usually accumulate in the rhizomes of giant reeds and it is recommended that rhizomes are removed regularly to improve the phytoremediation (Fiorentino et al., 2017).

Arundo donax can contribute to restoring the soil ecosystem and in biomass production (Alshaal et al., 2013; Jámbor & Török, 2019). The plant has also been deployed to control soil erosion (Cosentino et al., 2015; Fagnano et al., 2015; Zucaro et al., 2015) while improving soil efficiency (Visconti et al., 2020). Since A. donax is tolerant to a wide range of environmental stresses, it is recommended to be propagated in marginal lands that cannot be used for other crops to increase ecosystem productivity without competition with food and fodder crops. Its cultivation will have positive effects on environmental quality, such as improvement of soil fertility and reduction in soil loss by erosion due to reducing soil erodibility and increasing vegetation cover (Eid et al., 2016). Previous research endeavors investigated the capability of A. donax for phytomanaging and phytoremediation of water sources (Soleimani et al., 2023) and contaminated soils in addition to its potential to be utilized as a plant-based feedstock (Cristaldi et al., 2020; El-Ramady et al., 2015; Lewandowski et al., 2003; Nsanganwimana et al., 2014).

Cropping A. donax can contribute to carbon sequestration and increase soil fertility. A study by Riffaldi *et al.* in 2010 indicated that the cultivation of A. donax in the long term, accompanied by less human interference, can improve the concentration of land organic matter and can increase carbon content in the soil. The plant retains more than 50% water, which indicates a low fire hazard. At the end of the growing season, the cell mass of the plant can be harvested while nutrients remain reserved in the rhizomes (Riffaldi *et al.*, 2010). Giant reeds can also be involved in improving nitrogen use efficiency in agricultural land areas (Dragoni *et al.*, 2015).

Throughout history, A. donax has been used for its agronomic, economic and environmental benefits. Since the ancient ages of human civilization, the plant has been used in making tools such as fences, flutes (Tshapa et al., 2021), paper (Caparrós et al., 2007), baskets, treillages, crude shelters, fishing snares, fencing for gardens, hunting tools, henhouses as well as for feeding cattle animals (Al-Snafi, 2015; Kumar et al., 2021), and in production of saxophones and clarinets (Danelli et al., 2020). Giant reed was used in horticulture as an ornamental plant (Antal, 2018). When the plant was first introduced to the United States, it was used for numerous applications such as roof thatching and traditional musical instrument production (Bell, 1997). Wood wind musical instruments are still made from the culms of A. donax and no satisfactory substitutes have been developed. This grass has also been used as a source of cellulose for rayon and is considered a source of paper pulp. A. donax can also contribute to composting with sewage and agricultural sludge to produce fertilizers (Pelegrín et al., 2018).

Arundo donax was believed to have been used by Egyptians thousands of years ago. According to Boulos & Fahmy (2007), grasses played a major role in the daily life of ancient Egyptians: agriculture, industries, roofing purposes, houses or shelter places and cattle yards, artwork, fishing rods and other activities. It was also used in wrapping certain mummies; baskets, mats and other objects.

Rods of *A. donax* are used in interior architecture, furniture design and ceiling clad-ding. Culms are used as appropriate thermal insulators and sound absorbers as they prevent echoes, especially when they are used as an integrated building unit (Noaman, 2018). The plant contributes also to various industrial and medicinal applications (Al-Snafi, 2015). Its biomass can also be involved in the production of biopolymers (Fiorentino *et al.*, 2017). A study has also managed to produce silica nanoparticles from giant reed to be used in applications as a photocatalytic degradation dye (Easwaran *et al.*, 2022). Giant reed has also been successfully subjected to multiple biogenic waste valorization to synthesize levulinic acid and phenol-based anti-oxidants of high pharmaceutical value (Licursi *et al.*, 2018).

Giant reed has also been reported to fulfill multiple medical and pharmacological applications, especially in folk medicine. In times of antiquity, the rhizomes were used in popular medicine. The rhizome of *A. donax* has been used throughout human history as a diuretic, a skin curer and to heal long-term fever (Kumar *et al.*, 2021). The plant has also been used as a sudorific, a moisturizer (Al-Snafi, 2015), an antilactant as well as for the treatment of dropsy (Al-Snafi, 2015; Ovez, 2006). Its extract has been also cited to attain a notable antibacterial effect (Sharma *et al.*, 2020). One of the lectins extracted from *A. donax* roots was indicated to be contributed to curing tumors (Kaur *et al.*, 2005).

It's believed that *A. donax* has been used in different cultures as a psychedelic drug capable of granting altered states of spiritual consciousness. The plant is mixed with the Harmal plant (*Peganum harmala*) to produce a drink correspondent to the well-known "Ayahuasca" of Latin America. This spiritual practice could find its origins in the ancient ritual of drinking soma of lore (Ghosal *et al.*, 1969). A diversity of tryptamines such as N,N-dimethyltryptamine, bufotenine and 5-Methoxy-N,N-dimethyltryptamine have been extracted from the rhizomes of the plant, which are known to possess psychedelic effects (Al-Snafi, 2015).

Arundo donax has recently been considered to be a highly promising bioenergy source. It's not an edible plant so it's classified as a second-generation source of biofuel (Lemons e Silva et al., 2015). Cultivating giant reed can be achieved without competition with edible crops as it can successfully grow in marginal lands (Danelli et al., 2020; Kassem et al., 2024; C. M. J. Williams et al., 2009). Competition with food crops for irrigation water and nutritive fertilizers can also be avoided as the plant can grow in relatively dry and infertile soil conditions (Alshaal et al., 2013). Giant reed is a very productive plant with a high growth rate. It can grow over five cm a day under optimum conditions (Balogh et al., 2012). This high growth rate makes the plant a suitable candidate for high biomass-based biofuel production. Biofuel is extracted from the lignocellulosic biomass of A. donax. The dry mass is treated to produce lignin and sugar undergoing fermentation (Corno et al., 2016).

Various studies cited *A. donax* as one of the most promising crops for the production of biomass (Jámbor & Török, 2019). Other endeavors focused on the balance of energy during the usage of lignocellulosic materials as crude fiber production of biomass among crops produced in agricultural systems (Venturi & Venturi, 2003). Jámbor & Török (2019) suggested that *A. donax* possesses the preeminent attributes amid the category of perennials. Giant reed is widely utilized in America for producing biofuel in large quantities, alongside, *Miscanthus giganteus*, canary grass, switch grass, and alfalfa (Gupta *et al.*, 2014). With such high tolerance to various stresses (Cocozza *et al.*, 2020; Kassem *et al.*, 2024; Lino *et al.*, 2023; Sánchez *et al.*, 2016; Tshapa *et al.*, 2021), the plant is regarded as an ideal solution for cheap cultivation of biomass yield to be used in bioenergy production.

Nackley et al. (2015) claimed that A. donax alongside Miscanthus giganteus are the best highly efficient biofuel crops. Nevertheless, they indicated that A. donax could be considered disadvantageous because of the invasive behavior contributed to it. Arundo donax has the advantages of economical sustainability (production of biomass and profit) as well as being socially friendly (carbon neutrality and the exemption from competition with food crops), yet the plant is not perfect when it comes to the environment, mainly because of its hunger for fresh water and its invasive impact against the biodiversity of native vegetation (Nackley, 2015). Prochnow et al. (2009) investigated grassy locations as sources of biomass production. They cite A. donax amid the highly efficient grasses (Prochnow et al., 2009). Compared to other biofuel crops, A. donax is rated very high. Laurent et al. (2015) drew out valuable information using statistics gathered from previous scientific endeavors including thirty-six various bioenergy plants. Their results indicated that A. donax and Pennisetum purpureum showed higher productivity than the vast majority of correspondent candidates.

Arundo donax is a very productive and resilient crop. Its ability to perform photosynthesis using solar energy surpasses other similar biofuel species (Rossa *et al.*, 1998). Due to this outperformance, the European continent expects to increasingly depend on the plant as a source of biomass (Fabbrini *et al.*, 2019). Using research data from farms in the Mediterranean region, Jámbor & Török (2019) drew attention to the biomass economic potential of *A. donax* cultivated in marginal and waste lands. These reasons encourage the usage of the plant through cultivation in Egypt and other Mediterranean countries as a source of clean cheap bioenergy. Such technology can display improvement to the national economy while participating in converting to green lifestyle in Egypt by mitigating pollution and climate change caused by traditional fossil fuel.

We believe there is a massive research gap yet to be covered regarding the economic potential of *A. donax* as a source of clean energy compared side by side with correspondent green energy sources. Scientific ventures are much required to make head-to-head efficiency comparisons between production systems of giant reed against other renewable energy production systems as solar energy and wind energy. This includes profiles as: cost, implementation time, feasibility, fitness to specific regions and countries, expected energy outcome, sustainability, possible aspects of impact on the environment.

2.7 *Reproductive behavior and phenology*

Research regarding the reproductive behavior of the plant is often conflicting (Danelli et al., 2020). The plant is seedless in Europe (Mariani et al., 2010), Asia (Mariani et al., 2010), the United States (Balogh et al., 2012), and the Australian continent (C. M. Williams et al., 2008). Various research suggested that giant reed seeds are usually nonviable. Although the plant's inflorescence carries myriads of flowers that are characterized by hermaphroditism, it is claimed that the plant propagates exclusively using agamical manners (Ceotto & Di Candilo, 2010; Decruyenaere & Holt, 2001). According to Balogh et al. (2012), the giant reed behaves as a clonal plant that reproduces using asexual means through the dissemination of its fragments. The viability of seeds was never proven and genetic fingerprinting suggested a single original genetic clone in the United States. This outcome solidifies the theory of exclusive asexual propagation of A. donax. Johnson et al. (2006) cited the rare fertility of giant reed seeds. It was reported that the plant usually propagates by rhizomes (Assirelli et al., 2013). Though it is widely indicated that the seeds of A. donax lack viability in most regions, it is reported that the plant had previously managed to grow in different areas using seeds gathered from the Asian continent (Mariani et al., 2010).

Danelli *et al.* (2020) suggested that this inability of seeds to reproduce is due to multiple reasons. The sterile seeds of the plant may be due to the inability of megaspore mother cells to perform cellular division. It is suggested that the reason for *A. donax* seeds sterility can be rooted in alterations in gametogenesis, fertilization and post-fertilization (Nikhade & Makde, 2014).

Flowering of giant reed happens after intervals of several years. This is a feature that solidifies the theory of an exclusive vegetative manner of propagation. New colonies are established as shoot-producing rhizomes spread out extensively underneath the ground (Speck, 2003). New growth can then be achieved by simple division from the colony as older stems fall and are torn on the floor. Thus, segments of culms reestablish themselves and create a new colony. It's reported that heavy rains during wet winter seasons can lead to flash floodings, causing fragments of reed rhizomes to get broken and disperse along flowing streams. This is the reason populations of reed species usually expand getting further from sources of water streams (Else, 1996).

Seeds of *A. donax* collected from different locations in Egypt had proven non-viable and had no germination (Kassem, 2023). This suggests that giant reed populations in Egypt, most probably, depend of vegetative methods to propagate via root divisions. Thus, plant segments behave with the tendency to fall and establish themselves forming new colonies. Balogh *et al.* (2012) agreed on this dispersal by fragments. As various researchers suggested, the hermaphrodite flowers of the plant are not used for reproduction (Ceotto & Di Candilo, 2010; Decruyenaere & Holt, 2001). It is suggested hitherto that further research can shed light on the reproductive behavior of giant reed especially with the consideration of its unmatched ability to spread over large distances.

Patterns of growth, as well as flowering phenology, are correlated to different plant attributes such as density of leaves, relative growth rate in addition to hollow ratio (Fabbrini et al., 2019; Sun & Frelich, 2011). Flowering usually takes place from June to December (Pilu et al., 2012). Other researchers suggest the plant flowers in late summer (Johnson et al., 2006). Saltonstall et al. (2010) reported that A. donax flowers between August and October. In the north Mediterranean the plant usually flowers from late summer to early autumn (Pilu et al., 2012). This chronological shift in phenological phases could possibly be due to adaptation to different climatic conditions as well as the probable presence of different varieties (or at least gene pool) of the plant. The plant in Egypt flowers in autumn and winter (Kassem, 2023). The plant manages to co-ordinate the flowering phase after the termination of the growth season during the beginning of autumn and throughout winter. It may stop growth in winter due to low temperatures (Angelini et al., 2009).

2.8 Cultivation of giant reed

Arundo donax has been cultivated over human history due to the great variety of applications and services the plant has. Its cultivation of giant reed can be traced back about 5000 years (Al-Snafi, 2015). In Egypt, it has been largely cultivated in different parts since remote times, especially along canals and around the fields as a fence plant and for sheltering the crops from winds and supporting grape plantations. Cultivation of giant reeds should be performed with intensive attention due to its invasive behavior (Jámbor & Török, 2019).

A new plantation of giant reed needs a maximum of five years to grow and build up biomass before the production of a principal yield of lofty standards. Cultivators usually choose and cut the quality reeds that suit intended applications during the winter season, when the reeds are two or three years of age. Through the process of harvesting, any canes that are so old for use are usually eradicated to permit a more ideal growing environment for the harvest of the next year (Jámbor & Török, 2019). The cultivation of giant reed depends on their vegetative reproduction and it can be improved using cutting the stems in single nodes (Cavallaro *et al.*, 2019). Another method of improving the yield is by feeding the cultivated plants with nitrate and ammonium as sources of inorganic nitrogen especially in wet land cultures (Tho *et al.*, 2017).

Arundo donax cropping systems have great importance as they provide growers with a valuable source of multiple applications in addition to their environmental value in the global warming mitigation of gas emissions, phytoremediation of polluted soils and controlling soil erosion (Cosentino et al., 2015; Fagnano et al., 2015; Nsanganwimana et al., 2014; Zucaro et al., 2015). Ideal harvesting time is from autumn to mid-winter (Borin et al., 2013) or during winter months (Cosentino et al., 2006) when the growth season ends (Angelini et al., 2009). Biomass is the highest in this period (Nassi o Di Nasso et al., 2010). These recommendations are following suggestions that the flowering season is in autumn and winter just after the growth season (Kassem et al., 2024). Handling cultivated giant reed may vary vastly. This is decided according to the preference of each cultivator as well as depending on the intended application. Growers usually tie new reeds together in massive bunches with undamaged plant parts. Tied bunches are thereafter pulled together with bottom parts spread away creating a pyramid form. They may also be stocked together using posts. Giant reed growers have the freedom to protect their newly cultivated reeds under trees canopy or other shelters.

To ensure sustainability, cultivating giant reed requires some measurements. Best economic schemes for giant reed farming can be achieved through the management of grasslands, using conventional farm machinery as well as slight concentrations of mineral fertilization. Briquetting or compressing into pellets may also be required for combusting applications (Jámbor & Török, 2019). A. donax is resistant to rain and cannot be harmed by rainy hails. It's worth noting that soil type and environmental conditions can impact the quality and viability traits of giant reed populations (Kassem, 2023). Cultivating giant reed usually stumbles on its water resources consuming behavior (Tarin et al., 2013). However, there are methods to alleviate giant reed's thirst for fresh-water by adding products from wastewater sludge to the soil. This enables a remarkable enhancement in plant's water use efficiency. This technique is expected to facilitate efficient cropping of A. donax under resource restrictions caused by climate change (Cano-Ruiz

et al., 2021).

It is possible to argue that giant reed has high levels of sustainability when it comes to economics and revenue making due to its great productivity rates. The plant is also a very successful prospect in terms of socially sustainable development because of its carbon neutrality and ability to avoid competition with food crops. However, giant reed is deficient in environmental conservation due to its undesired impact on native biodiversity as well as consuming water sources (Jámbor & Török, 2019). In general terms, the cultivation of giant reed could be controversial due to its invasive behavior (Virtue et al., 2015). However, cultivation in wasteful poor regions and marginal lands can be very beneficial as it allows the overcoming of controversies regarding land use by producing an economic crop without risking invasive behavior or compromising food security (Bosco et al., 2016).

Conclusions

Arundo donax is a widespread grass that grows near fresh and brackish water sources. Plant breeds lack seed viability and usually propagate vegetatively. The plant has a remarkable adaptability to stress conditions. It can successfully thrive near sewage systems around polluted soils and water sources unsuitable for farming. Giant reed can also participate in a variety of ecosystem services by cleaning nearby water sources and improving the quality and fertility of the soil. The plant has a very promising future in biofuel production due to its high biomass production. Though a fierce invasive species, the plant can be controlled and cropped for its value. Highly efficient breeds of the plant are suitable for cultivation as a cheap clean source of renewable bioenergy. The plant is widely removed for its invasiveness. However, the efficiency of the plant can be harnessed to gain greater economic and environmental benefits. Thus, the plant may fulfill an eminent value considering its highly positive potential contribution toward various issues such as: the economy, sustainable development and mitigation of climate change. Much further scientific understanding of the plant is yet required to improve the efficiency of its exploitation whether in human made cultivations or in wild habitats.

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