Current Status and Trends in the Utilization and Research of Germplasm Resources of the Multipurpose Plant *Arundo donax*

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Abstract *Arundo donax* is a perennial grass species with a broad distribution and diverse potential applications. This review comprehensively examines its significant value in biomass energy production, ecological restoration, fiber utilization, as well as edible and forage applications, and systematically summarizes recent advances in the collection and preservation of *A. donax* germplasm resources, the breeding of new varieties and elite germplasms, genetic diversity assessment, germplasm identification, stress resistance mechanisms, and gene function exploration. In light of current challenges, including the unclear genetic background of *A. donax* germplasm, an incomplete evaluation system, and limited breeding innovation, this paper advocates for the establishment of an integrated collaborative development framework encompassing the entire chain of "preservation–evaluation–breeding–identification–utilization", aiming to provide high-quality resources to support the green and high-quality development of forestry ecological construction and biomass-related industries in China.

Keywords *Arundo donax*, Germplasm resource, Ecological restoration, Biomass energy, Stress resistance

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Arundo donax, a perennial herbaceous species within the genus *Arundo* of the Poaceae family, is extensively distributed across tropical, subtropical, and temperate regions. Both wild and cultivated forms are present throughout all provinces of China. Characterized by its imposing stature and graceful morphology, *A. donax* is commonly employed in landscape greening, particularly in waterfront environments such as riverbanks and lakeshores. This species exhibits strong adaptability, demonstrating tolerance to waterlogging, drought, and saline-alkaline soils. It is capable of rooting, sprouting, and attaining considerable height even in nutrient-poor substrates, thereby earning recognition as a pioneer species for low-lying saline-alkaline lands[1–2]. Furthermore, *A. donax* possesses phytoremediation potential, contributing to the purification and restoration of soils, wetlands, and wastewater contaminated with heavy metals, pharmaceuticals, and other pollutants[3-5]. *A. donax* exhibits robust growth potential, reaching maturity within one year and attaining heights of up to 6 m[6]. It possesses high biomass and fiber content, rendering it an excellent raw material for clean energy production. The fiber of *A. donax* is characterized by considerable length, making it an ideal resource for papermaking, thereby reducing dependence on wood-based materials. Additionally, it serves as a suitable substrate for cultivating edible fungi and as a source of high-quality animal feed. Within the framework of China's strategic focus on promoting the energy revolution, material innovation, and agricultural structural transformation, a comprehensive review of the current development, utilization, and research status of *A. donax* germplasm resources, alongside an exploration of the development pathways for its entire industrial chain, provides significant ecological, economic, and social advantages. This endeavor holds significant theoretical and practical importance for ensuring national energy security, mitigating pressures on feed and grain supplies, and promoting sustainable, green, and low-carbon development.

1 Development and utilization of *A. donax*

1.1 Ecological restoration and greening in challenging sites

Zeng Peng et al.[7] reported that intercropping *A. donax* with paper mulberry and mulberry in heavy metal-contaminated soils not only promoted plant growth but also increased the efficiency of heavy metal accumulation by the plants, concurrently enhancing soil enzyme activity. Through pot experiments, Bouabdallah et al.[8] observed that cadmium predominantly accumulated in the roots of *A. donax*, whereas lead was primarily translocated to the aerial parts, with the highest concentrations found in the leaves. Low cadmium concentrations (≤300 μg/g) exerted a stimulatory effect on *A. donax* growth, whereas higher concentrations inhibited its growth. A similar dose-dependent effect was noted for lead. Li et al.[9] conducted hydroponic experiments to investigate the response mechanisms of *A. donax* to individual and combined mercury and cadmium contamination. Their findings indicated that exposure to a single heavy metal slightly promoted the growth of *A. donax*, whereas combined heavy metal stress significantly inhibited its growth. The roots of *A. donax* demonstrated a strong capacity to accumulate mercury and cadmium but exhibited limited translocation of these metals to the aerial parts. Cadmium exerted a low-promoting effect and a high-inhibiting effect on the accumulation and volatilization of mercury. *A. donax* primarily mitigated mercury pollution through phytostabilization and phytovolatilization mechanisms, but its efficacy in cadmium remediation was limited.

Zhou Han et al.[10] investigated the impact of saline-alkali stress on the growth of *A. donax* Lvzhou No. 1, reporting a decline in overall plant height growth corresponding with increasing concentrations of saline-alkali solution. Li Jiurong et al.[11] conducted low-temperature stress tests to compare the cold resistance among five *Arundo* species, finding that Lvzhou No.3 exhibited the greatest cold tolerance. Liang Le et al.[12] examined the growth and physiological responses of *A. donax* under flood stress, demon strating that flooding conditions enhanced phenotypic development and that the plant maintained normal growth following continuous flooding for 4 months. Lino et al.[13] conducted a systematic review examining the growth potential of *A. donax* under various abiotic stressors, demonstrating that *A. donax* exhibited considerable tolerance to multiple adverse conditions, including drought, salinity, alkalinity,

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waterlogging, extreme temperatures, and heavy metal contamination. Ercoli et al.[14] investigated the combined remediation of pharmaceutical pollutants in wastewater using microorganisms and *A. donax*, reporting removal rates of clarithromycin (CLA) and diclofenac (DCF) as high as 84% and 95%, respectively. *A. donax* effectively absorbed and accumulated CLA predominantly in stems and leaves, and DCF primarily in roots. Nevertheless, exposure to high concentrations of these pharmaceuticals still inhibited root system growth.

1.2 Utilization of biomass energy

The National Development and Reform Commission and the National Energy Administration have jointly issued the *Action Plan for the Low-Carbon Transformation and Construction of Coal Power (2024–2027)*, which promotes the low-carbon transformation of existing coal-fired power units and the low-carbon construction of new units through methods such as biomass co-firing, green ammonia co-firing, and carbon capture, utilization, and storage, thereby enhancing the clean and efficient utilization of coal. *A. donax* has demonstrated considerable strategic value in fostering rural industrial revitalization, advancing green development, achieving carbon neutrality, and ensuring national energy security, and it has been designated as a key species for development[15]. As a novel energy crop, *A. donax* possesses a dry-basis carbon content exceeding 46% (high calorific value ranging from approximately 17.00 to 24.30 MJ/kg) and a relatively low ash content (3%–8%). Compared to traditional biomass fuels such as corn stalks and sawdust, *A. donax* exhibits superior combustion characteristics[16].

A. donax exhibits significant potential as a large-scale substitute for coal in heating and power generation applications[17]. Ma Ying et al.[18] investigated the co-combustion characteristics of *A. donax* and Yunnan lignite. Their single-fuel combustion experiments demonstrated that *A. donax* possessed a lower ignition temperature (approximately 100 °C lower than that of Yunnan lignite) and exhibited a more intense volatile matter combustion phase. Mody et al.[19] reported that the combustion behavior of biomass derived from *A. donax* in boilers closely resembled that of coal, while producing reduced emissions of NO_x and SO_2. Ortega et al.[20] identified *A. donax* as a highly promising raw material for biorefining, capable of generating high value-added products and bioenergy. Provided that its ecological risks are managed scientifically, *A. donax* can contribute positively to the development of a sustainable economic system. Beyond direct combustion for power generation, *A. donax* can be converted into high-value energy products through technologies such as pyrolysis and gasification, thereby broadening the diversity of its energy utilization pathways.

1.3 Utilization of fiber materials

In 2020, the Ministry of Ecology and Environment, the Ministry of Commerce, the National Development and Reform Commission, and the General Administration of Customs jointly issued the *Announcement on Matters Concerning the Comprehensive Ban on the Import of Solid Wastes*, which, effective January 1, 2021, completely prohibited the importation of foreign waste materials, including waste paper. This policy has imposed dual pressures and challenges on China's papermaking industry, specifically regarding raw material shortages and the imperative for green transformation. *A. donax*, a high-quality, fast-growing fiber plant, possesses several advantageous characteristics: it is native and renewable, does not compete with food crops for arable land, exhibits excellent fiber quality, and is well-suited for clean pulping processes. Consequently, it can serve as a substitute for imported waste paper, which carries higher pollution risks, thereby substantially reducing the environmental load and carbon footprint associated with pulping. This substitution supports the papermaking industry in achieving raw material localization, carbon reduction, and sustainable development.

Sheng Cuihong et al. developed a bio-enzyme pulping process utilizing *A. donax* stalks as raw materials (Patent No.: CN118639456A), producing pulp fibers with a fineness of ≤0.5 mm. This method not only reduces the consumption of chemical reagents but also offers advantages such as operational simplicity, low cost, and environmental sustainability. Xu Yanpeng[21] investigated the clean production process of biopulping from *A. donax* and demonstrated that acid-base pretreatment significantly increased pulp yield while enhancing the physical properties of paper, including tensile strength, ring crush strength, and tear resistance.

A. donax is an economical and versatile sustainable material with extensive potential applications in contemporary architecture[22]. Its fibers exhibit high tensile strength, making them suitable as raw materials for particleboard production[23].

1.4 Development and utilization for food and feed

A. donax serves as an excellent substrate for the cultivation of edible fungi, including wood ear mushrooms, shiitake mushrooms, and reishi mushrooms[6]. The crude protein content of *A. donax* is notably high, constituting 21.03% of its nutritional components, and it exhibits a relatively high degradation rate in the rumen, thereby representing a valuable high-protein forage source for herbivores[24]. Furthermore, the low levels of cellulose (309.16 mg/g, DW) and lignin (210.38 mg/g, DW) in *A. donax* enhance its palatability for fish, facilitating easier consumption and utilization by herbivorous fish. Consequently, *A. donax* is well-suited as a sustainable green feed in aquaculture systems[25].

2 Collection, preservation and variety breeding of *A. donax* germplasm resources

Several research institutes, universities, and companies in China have undertaken the collection and preservation of *A. donax* germplasm resources. The Chinese Academy of Forestry has gathered *A. donax* specimens from 21 geographical populations across 12 provinces, including Zhejiang, Sichuan, and Guangdong[26]. The China National Engineering Research Center for Juncao Technology at Fujian Agriculture and Forestry University has successively collected and introduced 12 *A. donax* varieties from Africa, Asia, Oceania, and other regions, designating them as the Lvzhou series, such as Lvzhou No.1 and Lvzhou No.2[27]. Following 13 years of extensive collection of wild *Arundo* species worldwide, Wuhan Landuo Biotechnology Co., Ltd. established a germplasm resource reserve comprising over 1,000 *A. donax* accessions (https://epaper.hubeidaily.net/pc/content/202601/18/content_337963.html), to support activities including production and operation of *A. donax*, variety selection and breeding, as well as large-scale cultivation and propagation.

The efficient preservation of germplasm resources is a fundamental prerequisite for variety breeding. In addition to ex situ preservation, tissue culture technology, as a central method of *in vitro* preservation, effectively addresses the challenges associated with ex situ preservation of *A. donax* germplasm, including extensive land requirements, vulnerability to environmental conditions, and low reproduction rates. Moreover, this technology provides essential technical support for the rapid propagation of superior germplasm and the development of new varieties. Previous studies have demonstrated that the type of explant and the hormone ratio are critical factors influencing callus induction and proliferation in *A. donax*, and these factors constitute the core elements for optimizing *in vitro* preservation and rapid tissue culture propagation systems. Chen Cen et al.[28] investigated the impact of various explant sources on the proliferation of callus in *A. donax*. They identified that when young leaves from field-grown seedlings were used as explants, the optimal culture medium was MS+1.0 mg/L 2,4-D+0.1 mg/L NAA+0.05 mg/L KT, resulting in a proliferation coefficient of 2.76. Conversely, when stem segments from tissue-cultured seedlings were employed, the most effective medium was MS+0.5 mg/L 2,4-D+ 0.5 mg/L NAA+0.05 mg/L KT, yielding a proliferation coefficient of 1.76. Ren Junhan et al.[29] utilized tender stem segments from polyploid *A. donax* and demonstrated that the combination of MS+0.25 mg/L 6-BA+1 mg/L 2,4-D effectively induced loose callus formation and significantly reduced the induction period. These studies offer valuable technical approaches for the *in vitro* preservation of *A. donax*.

In 2021, the National Forestry and Grassland Administration included *A. donax* in the list of protected plant varieties. By 2025, a total of 11 new varieties had been authorized (https://www.forestry.gov.cn/), with all variety rights held by enterprises. The breeding efforts were primarily directed towards meeting industrial demands, encompassing multiple application scenarios such as energy utilization, stress resistance, high quality, high yield, and fiber utilization. Xian Kanghua et al.[30] utilized axillary bud stem segments of *A. donax* introduced from Hungary as explants and systematically optimized the concentration of growth regulators in MS medium, thereby establishing an efficient culture system that included axillary bud induction, subculture proliferation, and root development. Similarly, Liu Shuyan et al.[31] employed stem segments of polyploid *A. donax* containing axillary buds and identified the optimal medium composition and hormone ratios through experimental screening. This work successfully established a comprehensive and efficient "one-step seedling" tissue culture propagation system for polyploid *A. donax*. These studies not only enhance propagation rates but also provide robust technical support for the rapid expansion and stable maintenance of superior *A. donax* varieties.

3 Evaluation and identification of *A. donax* germplasm resources and regulatory mechanism of functional traits

Molecular marker technology is extensively utilized in the evaluation and identification of *A. donax* germplasm resources. Ye Jianjun et al.[32] performed cluster analysis on nine materials, including Lvzhou No.1 through Lvzhou No.8 and *A. donax* 'Versicolor,' employing RAPD markers. Their results indicated that *A. donax* 'Versicolor' exhibited a relatively distant genetic relationship with the eight Lvzhou materials. Among these, Lvzhou No.5 and Lvzhou No.6 demonstrated unique genetic backgrounds. Zeng Hanyuan et al.[33] analyzed 11 populations of *A. donax* across six provinces in China using ISSR molecular markers. The study revealed that *A. donax* possessed high genetic diversity, with genetic differentiation predominantly occurring among populations, whereas differentiation within populations was comparatively limited. Sun Yuanchang et al.[27] confirmed that the Lvzhou series all belong to *A. donax* through analysis of the ITS2 sequence and direct homologous low-copy genes. Evangelistella et al.[34] developed EST-SSR markers. These studies provide a theoretical foundation for the evaluation, identification, and breeding improvement of *A. donax* germplasm resources.

Significant progress has been made in elucidating the regulatory mechanisms underlying the response of *A. donax* to various abiotic stresses. Barbero et al.[35] employed transcriptomic approaches to identify genes associated with heat and water stress responses in *A. donax*. Rotunno et al.[36] developed a microRNA-target gene regulatory network to characterize the response to salt stress in this species. Ren et al.[37] completed the first chromosomal-level genome assembly of *A. donax*, clarifying its genomic characteristics as a homologous heterologous tetraploid ($3n=9x=108$). Their analysis revealed two whole-genome duplication (WGD) events during its evolutionary history and identified 611 expanded gene families closely linked to multiple stress responses, including drought, oxidative stress, osmotic stress, low temperature, and heat shock. Sun Yuanchang et al.[27] utilized transcriptome sequencing to perform selective stress analyses on Lvzhou No.1 and Lvzhou No.3 cultivars, identifying a series of positively selected genes related to transcriptional regulation, stress resistance, and development. These studies provide a critical theoretical foundation for understanding the molecular mechanisms underlying stress resistance in *A. donax*.

Significant progress has been achieved in the identification of functional genes and regulatory factors. Evangelistella et al.[34] identified key genes involved in the biosynthesis of lignin, cellulose, purine, and thiamine, as well as in carbon fixation and stomatal development, through the application of transcriptome sequencing technology. Shao Ensi et al.[38] screened genes associated with biomass yield and bioethanol conversion by comparing the transcriptomes of *A. donax* specimens from different geographic regions (Shandong and Fujian). Zhong Nan et al.[39] performed a comparative transcriptomic analysis of Ninglu No.1 and Lvzhou No.1 cultivars, revealing that transcription factors such as AP2/ERF, B3, bHLH, and bZIP were closely linked to the growth advantages observed in *A. donax* seedlings. These studies have established a foundation for the genetic improvement of *A. donax* traits.

4 Challenges and discussions

A. donax possesses considerable value across multiple domains, including ornamental use, ecological restoration, biomass utilization, edible and feed applications, thereby representing a promising multifunctional industrial crop. Although some advancements have been made in its application and research, a comprehensive national survey of wild germplasm resources for *A. donax* has yet to be conducted. Consequently, there is a lack of thorough assessment regarding the genetic diversity of the overall wild germplasm, as well as insufficient evaluation and identification of superior and unique germplasm resources. Furthermore, a scientifically sound and systematic core germplasm screening system has not been established. These limitations significantly hinder the exploration and development of *A. donax* germplasm resources and the breeding of improved varieties, thereby impeding the fulfillment of diverse industrial demands such as ecological restoration, energy production, and papermaking.

Therefore, it is imperative to conduct a comprehensive national survey of the wild germplasm resources of *A. donax* at the earliest opportunity to obtain an accurate understanding of the current status. This should be followed by a systematic assessment of the genetic diversity of *A. donax*, alongside the evaluation and screening of outstanding and unique germplasm resources. Particular attention should be given to germplasm from the "Three North" regions and ecologically fragile areas, including coastal tidal flats, saline-alkali lands, inland heavy metal mining sites, and severely polluted wetlands. Furthermore, in-depth research is required to elucidate the regulatory mechanisms underlying biomass production, fiber quality formation, remediation of heavy metal and pharmaceutical pollution, and responses to abiotic stress in *A. donax*. Furthermore, it is essential to develop a comprehensive system for the phenotypic and genotypic identification and evaluation of superior *A. donax* germplasm resources, as well as to establish a core germplasm resource repository (garden). Efforts should also focus on the creation of superior germplasm tailored to diverse application scenarios and the targeted cultivation of specialized, high-quality *A. donax* varieties with independent intellectual property rights in China. These initiatives will establish a robust material foundation and offer technical support to facilitate the comprehensive utilization of *A. donax* throughout the entire industrial chain across various sectors.

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