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Selection and evaluation of suitable tree species in dry and dusty mining areas of Northwest China

Xiaofang Zhu[1] · Bing Cao[1] · Siming Zhao[1] · Xing Wang[1] · Hao Zhang[1] · Deping Gao[1] · Yongfeng Duan[1]

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Abstract To select drought-resistant and dust-tolerant native species suitable for use in the rehabilitation of major coal bases in northwest China, nine tree species were identified for growth rates, biomass, harm index, and physiological indices under drought and high dust stress conditions. The results showed that, in the dust resistance index system, the order was *Caragana korshinskii* > *Amorpha fruticosa* > *Sabina vulgaris* > *Hedysarum scoparium* > *Tamarix chinensis* > *Ammopiptanthus mongolicus* > *Ulmus pumila* > *Caryopteris mongholica* > *Elaeagnus angustifolia*. In a comprehensive drought and dust resistance index system, 14 indices (such as shoot length, stomatal conductance, and peroxidase) had the larger weight indices. The drought and dust resistance order of the tree species was *Caragana korshinskii* > *Ulmus pumila* > *Amorpha fruticosa* > *Sabina vulgaris* > *Caryopteris mongholica* > *Ammopiptanthus mongolicus* > *Hedysarum scoparium* > *Tamarix chinensis* > *Elaeagnus angustifolia*. This study provides effective strategies and references for selecting suitable tree species for arid mining sites in China, and also for the revegetation of coal mining sites worldwide.

Keywords Coal mining · Species selection · Drought resistance · Dust resistance · Evaluation index system

Introduction

Northwest China is a large arid region with a dry atmosphere, deserts, sandstorms and fragile ecology (Zhu et al. 2016; Roy et al. 2020). Drought is the major factor limiting plant growth and productivity due to climate change, rapid industrialization, as well as the over-exploitation resources in northwest China (Li et al. 2010; Nezhadahmadi et al. 2013; Na and Jiang 2018; Zhao et al. 2018; Roy et al. 2020). Annual precipitation varies from 410 mm in the east, 230 mm in the west and in some places, below 50 mm, while evaporation may vary from 1500 to 3600 mm per year (Yi and Li 2011). The low precipitation and high evaporation produce dry air and dehydrated soils, resulting in water deficits for plants and affecting their normal growth and development (Sun et al. 2003; Li et al. 2010; Wang et al. 2015). Most cropland is dryland rain-fed farming, and water scarcity is the biggest challenge for local agriculture development in this region (Li et al. 2010).

Drought-resistant plants can generally tolerate long-term water shortages by developing natural mechanisms, from enhanced deep root growth to control of water loss in leaves (Hu and Kang 2005; Li et al. 2010; Tirado and Cotter 2010; Chang et al. 2018). Drought resistance mechanisms

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✉ Bing Cao
bingcao2006@126.com

✉ Xing Wang
xingwang1984@foxmail.com

[1] School of Agriculture, Ningxia University, Yinchuan 750021, People’s Republic of China

are usually studied from the morphological structure, and physiological and biochemical indices of plants (Farooq et al. 2009; Li et al. 2010; Tirado and Cotter 2010; Anjum et al. 2011; Nezhadahmadi et al. 2013). In northwest arid regions, soil-water deficiency is one of the major factors restricting plant establishment and survival (Ji et al. 2006; Li et al. 2010; Wang et al; 2015; Roy et al. 2020). An et al. (2007) found that leaf area and the growth rate of new branches were the lowest under severe drought compared with those under adequate water conditions. Pan et al. (2003) reported that drought stress decreased plant biomass. Water deficiencies caused a notable reduction in growth-associated parameters (e.g., maximum height, stem diameter, root length and dry biomass) (Roy et al. 2020). Therefore, the selection of drought-resistant species has always been an important subject for vegetation introduction in northwest China (Li et al. 2010; Wang et al. 2015; Na and Jiang 2018; Zhao et al. 2018).

Coal mining has considerable impact on local ecosystems due to severe environmental and ecological problems, like vegetation damage, soil water contamination and air pollution at the mining sites and in the surrounding areas (Rocha-Nicoleite et al. 2018; Pietrzykowski 2019). Increasing demand of coal has led to adverse impacts on the natural environment and air quality, especially in north-western China (Li et al. 2010; Zhao et al. 2018). There have been numerous studies on dust resistance of plants (Wang et al. 2014; Aliya et al. 2015; Zhang et al. 2015a; Nurmamat et al. 2017; Shah et al. 2018). Most of these studies have focused on the dust retention of urban tree species (Joshi et al. 2007; Wang 2011b; Wang et al. 2014; Li et al. 2016; Tang 2017), and some research has focused on air pollutant adsorption in urban settings by different types of roadside vegetation, and found that plants with needles adsorbed more airborne particulates than broad-leafed plants with the same leaf area (Beckett et al. 1998; Prajapati and Tripathi 2008; Zhang et al. 2015a, 2015b; Shah et al. 2018). Only a few studies have looked at the selection of tree species for highly dusty, arid coal mine spoils (Grant et al. 2002; Pietrzykowski 2019). Coal mining sites in arid areas require species to be drought-resistant because of the shortage of water, and growth of trees has been seriously harmed because of dust and other pollutants caused by mining. Tree species need not only withstand water shortages but also the hazards of particulate matter such as severe dust (Schleicher et al. 2011; Wang 2011a; Losfeld et al. 2015; Zhang 2016). These two factors are critical since species with enhanced drought resistance may not show strong dust resistance. The success of revegetation depends on the species and their adaptation to newly formed reclaimed mining soils. In this study, species were evaluated for their drought and dust resistance. There have been no studies on species selection for these attributes. We have hypothesized that (1) strong drought resistance species have strong dust resistance, (2) strong drought resistance species have weak dust resistance and (3) tree species with moderate drought resistance have strong dust resistance.

Nine native species (*Caragana korshinskii*, *Tamarix chinensis*, *Amorpha fruticosa*, *Hedysarum scoparium*, *Ammopiptanthus mongolicus*, *Caryopteris mongolica*, *Sabina vulgaris*, *Ulmus pumila*, and *Elaeagnus angustifolia*) were selected to determine their relative drought and dust resistance. These species are widely planted in northwest China. Due to extreme arid and cold environment, introduced or exotic species may not adapt to the local climate. Native species, like nine species we selected in the research, may be suitable for the local arid environment. However, these species showed different adaptations under different mining and dusty environments. Species in field pots were used to monitor growth, physiology and biomass. Principal component analysis (PCA) and membership function methods were applied to evaluate and compare drought and dust resistance of species.

Materials and methods

Study area

Dust resistance experiments were carried out in Ningxia at the Yangchangwan Coal Mine (106°35′–106°38′ E, 37°59′–38°03′ N) of the Shenhua Ningxia Coal Industry Group, and drought resistance tests were monitored at a nearby farm (105°49′–106°22′ E, 38°26′–38°38′ N). The distance between the drought and dust resistance test sites is 68 km. Climate of the two sites are similar. Ningxia has a temperate, arid climate, with an average annual temperature of 8.8 °C. Annual maximum and minimum temperatures were 41.4 °C in 1953 and -28.0 °C in 1954. The average frost-free period is 167 days. Precipitation mostly occurs from July to September with an annual average of 206.3 mm, accounting for 76% of the annual rainfall. Average annual evaporation is 1470.1 mm. The main wind direction is west-northwest, and the average wind speed is 3.1 m/s; the maximum is up to 20 m/s. Soil texture is sandy loam and annual average soil moisture content is 8.4% in 0–300 cm depth. Soil pH was between 8.4 and 9.2, and total salt content was 0.13–1.04 g/kg. Soil organic matter ranged from 0.15 to 1.47%. Total nitrogen, alkali-hydrolyzable nitrogen, and available phosphorus and potassium ranged from 0.3 to 1.0 g/kg, 25.0 to 88.6 mg/kg, 1.3 to 32.9 mg/kg, and 73.3 to 190.0 mg/kg, respectively.

The experiment was carried out from April 2018 to October 2019. One-year old potted seedlings of *Caragana korshinskii*, *Tamarix chinensis*, *Amorpha fruticosa*, *Hedysarum scoparium*, *Ammopiptanthus mongolicus*, *Caryopteris mongholica*, *Sabina vulgaris*, *Ulmus pumila*, and *Elaeagnus angustifolia* were selected. The size of the pots was upper diameter 580 mm, lower diameter 450 mm and height 520 mm. The potting soil was simulated soil of waste rock from the Lingwu Yangchangwan Coal Mine site. In April 2018, the selected seedlings were planted on the site for drought resistance and dust retention tests (Fig. 1).

In the drought resistance test, a progressive water stress treatment was carried out using a pot-water control method and single-factor design was adopted. A natural drought treatment group and control group were established. All plants were fully irrigated three days before the test to ensure that the soil in each pot was saturated. Watering in the treatment group ceased after three days and renewed after 30 days of drought stress. The seedlings in the control group were watered every seven days. The PCA method was used to calculate the weight of each index and to establish the tree drought resistance evaluation index system (Xie and Hu 2016; Guo and Wang 2018). For the dust resistance test, we selected the dust-contaminated coal-mining site (waste rock field) for the pot experiment. Dust retention per unit area was 1.08–2.76 g/m^2/week; the plants were watered every seven days. After rainfall (> 15 mm), the relevant indices were monitored. We replicated the test with 10 pots of each seedling species.

Measurement indices

Growth indices and biomass

At the beginning and end of the two tests, growth indices (height, ground diameter, shoot length, and crown breadth) were measured to calculate the net growth (growth index value $_{\text{at the end}}$-growth index value $_{\text{at the beginning}}$). Three whole seedlings were removed from each pot to measure biomass of the stems, leaves, and roots. Leaf biomass ratio (leaf dry mass/plant dry mass), root biomass ratio (root dry mass/plant dry mass), stem biomass ratio (stem dry mass/plant dry mass), root shoot ratio (root dry mass/upper ground dry mass), and the length of the main root system were calculated (Ma et al. 2010).

Physiological indices

Physiological growth parameters influence the growth of plants, and this study consisted of photosynthetic and water physiological indices. Twenty-eight drought-resistant physiological indices were measured, including photosynthetic parameters, water consumption, leaf water saturation and deficit values, superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and other enzyme activities. Twenty dust-resistant physiological indices were recorded,

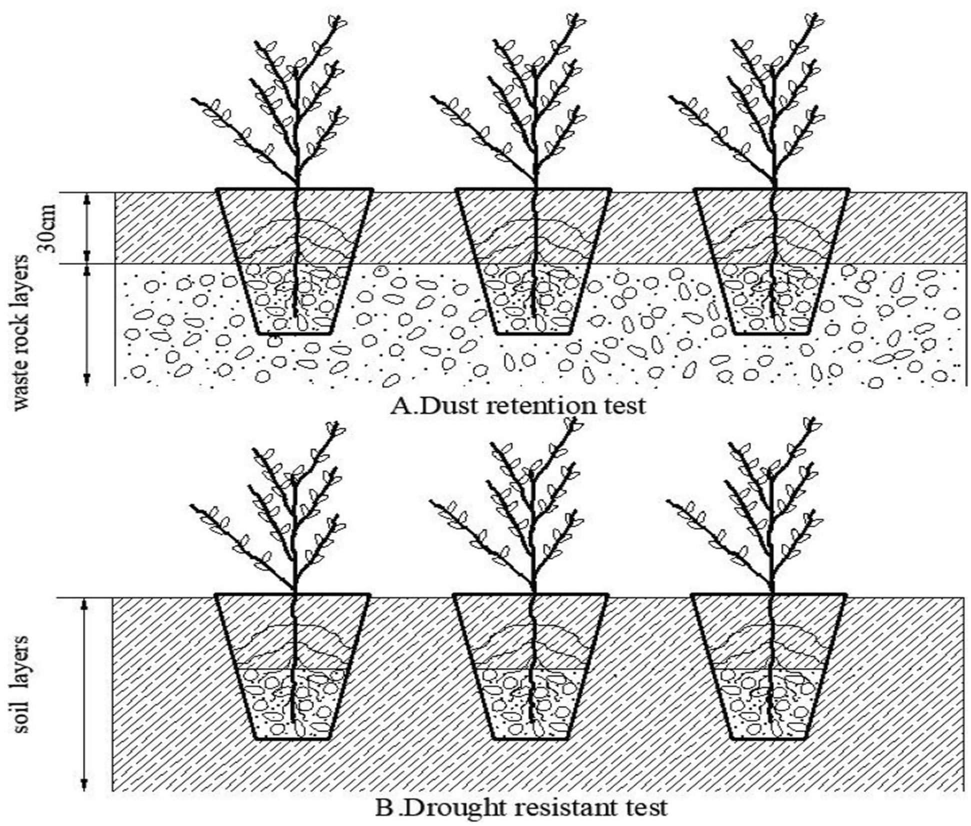

Fig. 1 Schematic diagram of potted plant tests

including stomatal conductance, plant water content, leaf relative water content (RWC), relative water deficit (RWD), transpiration rate, photosynthetic rate, intercellular CO_2 concentration and water use efficiency.

At the beginning, middle, and end of the test, with the TARGAS-1 portable photosynthesis analyzer (PP Systems, Amesbury, MA, USA), three leaves of different plants on the sunny side from 9:00 to 11:00 a.m. were randomly selected to measure physiological indices of the different species. Leaf water content [(leaf fresh mass-leaf dry mass)/ leaf fresh mass], plant water content [(fresh plant mass-dry plant mass) /fresh plant mass] were calculated. Soil moisture content was measured every half hour using a Multi-point Soil Temperature and Humidity Recorder (TZS-2XG). Leaf relative water content (RWC; Eq. 1) and relative water deficit (RWD; Eq. 2) were determined by the drying method. Fresh plant leaves were cut, weighed fresh (Wx) and soaked in ionized water. After 24 h, leaves were removed, surface dried, weighted saturated (W_b), and transferred to an oven for 15 min at 105 °C and 90 °C until constant weight (W_h).

$$(\mathrm{RWC})\% = (\mathrm{Wx} - \mathrm{W_h})/(\mathrm{W_b} - \mathrm{W_h}) \times 100\% \quad (1)$$

$$(\mathrm{RWD})\% = 1 - \mathrm{RWC}\% \quad (2)$$

Leaf water retention capacity was measured by the in vitro leaf weighing method. Ten effective leaves (with some leaf sheaths) were cut every seven days after fully watering, weighed fresh immediately, and then dried in an oven at 105 °C for 15 min and again for 48 h at 90 °C to obtain the dry weight. The calculation of leaf water retention capacity was fresh weight-dry weight and was calculated in six consecutive weeks for each species to analyze water retention capacity.

Dust retention

Thirty leaves were randomly sampled on day 7 after rainfall and the amount of dust retained measured by the cleaning method (Guo et al. 2007; Aliya et al. 2015). Leaf area (cm^2) was measured with a portable leaf area meter, and recorded as S_1, S_2,…,S_{30}. The washed leaves were dried and weighed. Dust retention was calculated using the following equation (Baidourela et al. 2015):

$$\text{Dust retention per unit leaf area}(\mathrm{g/m^2/week}) = \frac{\mathrm{M_1} - \mathrm{M_2}}{\sum \mathrm{S}_i(\mathrm{i} = 1, 2, \ldots, 30)} \times 10^4 \quad (3)$$

$$\text{Dust retention per unit fresh leaf weight (g/g) } \mathrm{d_f} = \mathrm{M} / \mathrm{W_f} \quad (4)$$

where, d_f is the amount of dust retained per unit fresh leaf weight (g/g); W_f is the total leaf fresh weight of the sample (g); and, M is the total dust retention of all leaves of the samples (g).

Harm index

Plant harm index is a way to reflect and evaluate the leaf damage degree caused by diseases and insect pests (He et al. 2007). To observe the impact of dust retention on morphology, a classification standard for leaf damage caused by dust retention was established (Table 1). In the dust resistance test, we investigated and classified 10 leaves of different orientations (east, west, south, north) and parts (upper, middle, and lower) of each species according to the following harm degree indices (Panda and Kush 1995; He et al. 2007):

$$\text{Harmindex} = \frac{\sum (Harmgradeleaves * Harmgraderepresentativevalue)}{(Totalinvestigatedleaves * Highestharmgradevalue)} * 100\% \quad (5)$$

Survival rate

The survival rate represents the adaptability of seedlings. Wilting or dead plants were recorded every seven days since the drought test began. At the end of the experiment, the survival rate (number of dead plants/total plants) was calculated.

Table 1 Evaluation standard for leaves under dust resistance stress

Classification of harmed leaves (value)	Harmed symptoms
0	Leaves were green and normal
1	The leaves were green with individual discolored spots or slight wrinkles and curls
2	The fading area of the leaf reached 1/3 of the leaf area, and the leaves were obviously curled
3	Above 3/4 area of the leaves were withered and severely curled
4	The leaves were all withered or completely curled and easily broken
5	Leaves fell off

Table 2 Physicochemical properties of potted soil

Soil	pH	Conductivity (ms·cm^{-1})	Organic matter (g·kg^{-1})	Total Nitrogen (g·kg^{-1})	Total Phosphorus (g·kg^{-1})	Alkaline Nitrogen (g·kg^{-1})	Available Phosphorus (g·kg^{-1})	Rapidly available potassium (g·kg^{-1})
Content	8.81	1.50	1.97	0.09	0.11	41.9	7.69	120.30

Results

Experimental micro-environment and leaf damage characterization

Soil physical and chemical properties in the pot experiments are shown in Table 2. Table 3 shows the air particle concentrations in the drought resistance and the dust resistance experiment site.

Table 3 The ambient air parameters in the drought resistance experiment site (farm) and the dust resistance experiment site (mining site)

Site	TSP (mg·m^{-3})	SO_2 (mg·m^{-3})	NO_x (mg·m^{-3})	$PM_{2.5}$ (μg·m^{-3})	PM_{10} (μg·m^{-3})
Farm	0.2	0.01	0.01	42.7	117.3
Mining areas	0.8	0.03	0.02	198.4	3055.2

Note: TSP represents total suspended particulate

Table 4 shows the harm symptoms and grades of leaves from different species after dust retention, and the grades of the harmed leaves from left to right are 0, 1, 2, 3, 4, and 5. *Sabina vulgaris* was less affected by dust retention and only showed grade 0 and grade 1 harm symptoms.

Screening and evaluation of drought resistance of species

Establishment of evaluation index system for drought resistant species

Table 5 shows the weight of each index and drought resistance evaluation index system. The greater the weight, the

Table 4 Harm symptoms of leaves after dust retention

Grades of harmed leaves	0	1	2	3	4	5
A. fruticosa						
E.angustifolia						
U. pumila						
A. mongolicus						
S. vulgaris						

Grades of harmed leaves	0	1	2	3	4	5
C. korshinskii						
T. chinensis						
C. mongholica						
H. scoparium						

greater the importance of the index. Among these indices, root biomass ratio, root/shoot ratio, water consumption, proline (PRO) content, CAT content and SOD content had relatively large weight index (> 0.05), which were the main indices for the comprehensive evaluation of drought resistance of the species.

Comprehensive evaluation of drought resistance of tree species

Table 6 shows the drought resistance coefficients of 28 indicators of nine species. The contribution rates of the first seven indices were 26.6%, 19.1%, 17.0%, 12.6%, 10.9%, 7.1%, and 4.8%. Their cumulative contribution rate reached 98.1%.

Screening and evaluation of dust resistance of tree species

Establishment of evaluation index system for dust resistance

In a dusty environment, species reflect their adaptability through changes in morphology and biomass allocation. The amount of dust retained on the leaves directly reflects the pollution of the surrounding air, and the harm indices of the leaves reflect the harm situation of the species. Dust retention per unit leaf area and per unit leaf weight, stomatal conductance, main root system length, transpiration and photosynthetic rates, harm index, water use efficiency, and root biomass ratio had a relatively high weight index (> 0.05) and could be used as the main indices to evaluate the dust resistance of different species (Table 7).

Table 5 Drought resistance evaluation index system

Target layer	Criterion layer	Weight index	Index layer	Weight index
Drought resistance of species	Growth status index	0.2844	Plant height	0.0357
			Ground diameter	0.0022
			Shoot length	0.0092
			Crown breadth	0.0352
			Main root length	0.0433
			Leaf biomass ratio	0.0085
			Stem biomass ratio	0.0401
			Root biomass ratio	0.0564
			Root shoot ratio	0.0538
	Water physiological index	0.2541	Soil water content	0.0209
			Leaf water content	0.0343
			Plant water content	0.0165
			Water consumption	0.0826
			RWC	0.0491
			RWD	0.0427
			Water retention capacity of leaves	0.0079
	Adaptability index	0.0433	Survival rate	0.0433
	Stress resistance index	0.1134	Conductivity	0.0420
			MDA content	0.0158
			PRO content	0.0556
	Photosynthetic physiological index	0.1454	Transpiration rate Tr	0.0112
			Stomatal conductance Gs	0.0334
			Photosynthetic rate Pn	0.0333
			Intercellular CO_2 concentration (Ci)	0.0317
			Water use efficiency WUE	0.0358
	Biochemical index	0.1594	CAT content	0.0516
			SOD content	0.0644
			POD content	0.0434

Table 6 Eigenvectors and contribution rates of principal components in drought-resistant experiments

Indices		Eigenvectors of the principal component indices						
		Principal component 1	Principal component 2	Principal component 3	Principal component 4	Principal component 5	Principal component 6	Principal component 7
Growth status index	Plant height	– 0.0254	– 0.0338	0.1576	0.0406	0.1891	– 0.0068	– 0.0199
	Ground diameter	0.0868	– 0.0267	– 0.1157	0.0107	– 0.0089	– 0.2266	0.1678
	Shoot length	– 0.0136	0.0483	0.1380	0.0184	– 0.2046	– 0.1384	0.0714
	Crown breadth	– 0.0360	0.0661	0.1374	0.1567	– 0.0589	– 0.0602	– 0.0962
	Main root system length	– 0.0099	0.1279	0.0361	0.1579	0.0256	– 0.2112	0.0056
	Leaf biomass	0.0241	0.0678	0.0486	– 0.1044	– 0.0947	– 0.3293	– 0.1088
	Stem biomass	– 0.1113	0.0392	0.0353	– 0.1325	– 0.0172	0.0208	0.0908
	Root biomass	0.0940	0.0053	– 0.0348	0.1892	0.0119	0.0032	0.0821
	Root: shoot ratio	0.0916	– 0.0011	– 0.0377	0.1931	0.0080	– 0.0018	0.0977
Water physiological index	Soil water content	0.0786	– 0.0165	– 0.0994	– 0.1775	– 0.0329	– 0.0159	– 0.0681
	Leaf water content	– 0.0117	0.1468	– 0.0667	– 0.0118	0.0234	0.1730	0.2852
	Plant water content	– 0.0350	0.1210	– 0.1445	– 0.0021	– 0.0064	– 0.0161	– 0.0553
	Water consumption	0.1152	0.0545	0.0415	0.0567	0.0659	0.1120	– 0.0043
	RWC	0.1066	– 0.0247	0.0378	0.0372	0.0945	0.0613	– 0.3291
	RWD	– 0.1037	0.0466	– 0.0946	0.0694	– 0.0795	0.0260	0.0604
	Water retention capacity of leaves	– 0.0731	– 0.0512	0.0092	0.1221	0.1671	0.1334	0.2407
Adaptability index	Survival rate	0.0799	0.1346	– 0.0296	– 0.0470	0.0112	– 0.1218	– 0.0240
Stress resistance index	Conductivity	– 0.0187	0.1474	0.0608	0.0431	0.1034	– 0.1098	– 0.2060
	PRO content	– 0.0199	0.0877	0.0899	– 0.0333	– 0.2095	0.1531	0.1016
	MDA content	0.0309	0.0861	0.0515	– 0.0920	0.2031	– 0.0590	0.3032
Photosynthetic physiological index	Transpiration rate Tr	0.0230	0.0683	– 0.1295	0.1491	– 0.1241	0.0639	0.0938
	Stomatal conductance Gs	– 0.0399	0.0683	– 0.1390	– 0.0958	0.0612	0.0924	– 0.2285
	Photosynthetic rate Pn	– 0.0940	0.0508	– 0.0885	0.1251	– 0.0126	– 0.0473	– 0.1464
	Intercellular CO_2 concentration (Ci)	0.0776	0.0258	0.0364	0.0069	– 0.2091	0.2174	– 0.0581
	Water Use Efficiency	– 0.1288	0.0235	0.0161	0.0226	0.0278	– 0.0103	– 0.0340
Biochemical index	CAT content	0.0433	0.1361	0.0089	– 0.1048	0.1020	– 0.0315	0.2430
	SOD content	0.0488	0.0817	0.1329	– 0.0545	– 0.0478	0.2320	0.0484
	POD content	0.0069	0.1338	– 0.0100	0.0032	0.1147	0.1954	– 0.3342
	Characteristic root	7.4521	5.3453	4.7614	3.5173	3.0666	1.9922	1.3449
	Contribution rate (%)	26.6148	19.0905	17.0049	12.5617	10.9521	7.1148	4.8032
	Cumulative contribution rate (%)	26.6148	45.7053	62.7103	75.2719	86.2240	93.3389	98.1420

Comprehensive evaluation of dust resistance of tree species

Dust resistance coefficients were calculated, and the results show that the contribution rates of the first six comprehensive indices were 30.5%, 18.8%, 16.1%, 13.4%, 9.3%, and 7.1%, and the cumulative contribution rate reached 95.2% (Table 8). Thus, we transformed 20 individual indicators into new and independent comprehensive indicators CI_1–CI_6. Table 9 shows the D value of the comprehensive evaluation of dust resistance: *Caragana korshinskii* > *Amorpha fruticosa* > *Sabina vulgaris* > *Hedysarum scoparium* > *Tamarix chinensis* > *Ammopiptanthus mongolicus* > *Ulmus pumila* > *Caryopteris mongholica* > *Elaeagnus angustifolia*. *Caragana korshinskii* and *Amorpha fruticosa* had the best dust resistance and their D values were 0.5782 and 0.5139, respectively. The least dust resistant species were *Caryopteris mongholica* and *Elaeagnus angustifolia*.

Table 7 Dust resistance evaluation index

Target layer	Criterion layer	Weight index	Layer index	Weight
Tree species dust resistance	Growth status index	0.3209	Plant height	0.0003
			Ground diameter	0.0108
			Shoot length	0.0370
			Crown breadth	0.0282
			Specific leaf weight	0.0475
			Main root system length	0.0752
			Leaf biomass ratio	0.0281
			Stem biomass ratio	0.0103
			Root biomass ratio	0.0581
			Root shoot ratio	0.0254
	Water physiological index	0.0450	Leaf water content	0.0203
			Plant water content	0.0247
	Dust retention	0.2435	Dust retention per unit leaf weight index	0.1182
			Dust retention per unit leaf area	0.1253
	Stress resistance index	0.0621	Harm index	0.0621
	Photosynthetic physiological index	0.3285	Transpiration rate	0.0738
			Stomatal conductance	0.0829
			Photosynthetic rate	0.0636
			Intercellular CO_2 concentration	0.0475
			Water use efficiency	0.0607

Comprehensive evaluation of drought and dust resistance

Drought and dust resistance indices included seven primary indices and 48 secondary indices. Among these, shoot length (dust retention), stomatal conductance (dust retention), crown breadth (dust retention), POD content (drought resistance), stem biomass ratio (dust retention), and transpiration rate (drought resistance), SOD content (drought resistance), dust retention per unit weight (dust retention), photosynthetic rate (dust retention), water consumption (drought resistance), malondialdehyde (MDA) content (drought resistance), intercellular CO_2 concentration (drought resistance), CAT content (drought resistance), leaf water content (drought resistance) and survival rate (drought resistance) had a relatively large weight (> 0.03). These indices were used to evaluate and select drought and dust resistant tree species. The contribution rates of the first eight comprehensive indices were 22.3%, 18.5%, 14.9%, 13.3%, 10.4%, 9.9%, 6.4%, and 4.2%, and their cumulative contribution rate reached 89.0% (Support Table S1). Thus, we transformed 48 individual indicators into new and independent comprehensive indicators CI_1–CI_9.

Table 10 shows that, in arid areas with high dust levels but under irrigation, species may be selected based on the order of dust resistance: *Caragana korshinskii* > *Amorpha fruticosa* > *Sabina vulgaris* > *Hedysarum scoparium* > *Tamarix chinensis* > *Ammopiptanthus mongolicus* > *Ulmus pumila* > *Caryopteris mongholica* > *Elaeagnus angustifolia*. In the high dust areas without irrigation, tree species can be chosen for both their drought resistance and dust resistance: *Caragana korshinskii* > *Ulmus pumila* > *Amorpha fruticosa* > *Sabina vulgaris* > *Caryopteris mongholica* > *Ammopiptanthus mongolicus* > *Hedysarum scoparium* > *Tamarix chinensis* > *Elaeagnus angustifolia* (Table 10).

Discussion

The selection of tree species for afforestation and reforestation purposes is an important subject in forestry research. It is generally believed that, because of water shortages and large-scale mining activities in northwest China, species with good drought and dust resistance are key to survival under the harsh environment. Mining dust contributes to global climate change due to its role in the air and soils.

Table 8 Eigenvectors and contribution rates of principal components in dust-resistant experiments

Indices		Eigenvectors of the principal component indices					
		Principal component 1	Principal component 2	Principal component 3	Principal component 4	Principal component 5	Principal component 6
Growth status index	Plant height	0.025	− 0.097	0.222	− 0.016	− 0.189	− 0.237
	Ground diameter	− 0.114	0.041	0.191	− 0.046	0.124	− 0.086
	Shoot length	0.121	− 0.033	0.115	− 0.129	− 0.221	0.044
	Crown breadth	− 0.007	0.098	0.144	− 0.202	− 0.116	0.385
	Specific leaf weight	− 0.011	− 0.087	0.119	0.126	0.419	0.013
	Main root system length	0.09	− 0.021	− 0.045	0.064	0.168	0.454
	Leaf biomass	− 0.058	− 0.038	0.156	0.251	− 0.048	0.106
	Stem biomass	0.124	− 0.106	0.003	− 0.158	− 0.08	0.074
	Root biomass	− 0.034	0.241	0.079	0.035	0.079	− 0.115
	Root: shoot ratio	− 0.056	0.226	0.065	− 0.004	− 0.019	− 0.175
Water physiological index	Leaf water content	− 0.01	0.215	− 0.101	− 0.039	− 0.131	0.19
	Plant water content	0.003	0.136	− 0.188	− 0.143	0.073	− 0.184
Dust retention	Dust retention per unit leaf weight	0.117	0.15	0.043	0.114	0.047	0.046
	Dust retention per unit leaf area	0.123	0.122	0.034	0.095	0.146	0.176
Stress resistance index	Harm index	0.005	0.071	0.11	0.277	− 0.224	0.081
Photosynthetic physiological index	Transpiration rate	0.149	0.014	0.017	− 0.006	0.135	− 0.23
	Stomatal conductance	0.107	0.068	0.205	− 0.07	− 0.057	− 0.106
	Photosynthetic rate	0.085	0.017	0.145	− 0.186	0.26	− 0.024
	Intercellular CO_2 concentration	0.127	− 0.02	− 0.08	0.172	− 0.133	− 0.111
	Water use efficiency	− 0.136	− 0.037	0.096	− 0.12	0.002	0.2
	Eigenvalues	6.1	3.763	3.223	2.678	1.869	1.415
	Contribution rate (%)	30.5	18.816	16.114	13.391	9.345	7.074
	Cumulative contribution rate (%)	30.5	49.316	65.43	78.821	88.166	95.24

Heavy metals from mining sites cause serious water and soil contamination. In some cases, trees may grow normally with dust pollution but cannot and even may die in certain cases of severe air pollution, even if irrigation is sufficient. Stomatal conductance was heavily blocked by dust caused by mining activities (Singh et al. 2021). Therefore, the capacity of a tree species to withstand soil and air pollution needs to be given priority.

This research introduced multiple variables while incorporating complex factors into several principal components, which simplified the problem and obtained scientific and effective data. As a result, this study overcame the subjectivity of artificially determined weight index (Zhou et al. 2016). The D value is a dimensionless comprehensive evaluation constant of each species. This evaluation was relatively objective and reliable. The PCA method and membership function offer advantages for the selection of suitable tree species for planting in complex environments. These two methods have been used in numerous fields, such as theoretical physics, meteorology, psychology, biology, chemistry and engineering (Loska and Wiechuła 2003; Collard et al. 2010; Giuliani 2017; Koo et al. 2021). It is beneficial to apply them in the selection of drought-resistant and dust-resistant species in arid areas with high air and soil pollution. Based on these results, drought-resistant species might not have the capacity

Table 9 Comparison of comprehensive index values in dust resistant experiments

Variety	CI_1	CI_2	CI_3	CI_4	CI_5	CI_6	$U(X_1)$	$U(X_2)$	$U(X_3)$	$U(X_4)$	$U(X_5)$	$U(X_6)$	D value	Order
U pumila	3.0031	1.8346	3.6603	− 1.3468	0.3893	− 0.5618	0.3948	0.3987	0.3619	0.1573	1.0000	0.2148	0.4026	7
Caragana korshinskii	5.2477	1.7804	5.7658	− 1.6624	− 1.1033	− 0.5922	1.0000	0.3765	1.0000	0.0000	0.0000	0.1942	0.5782	1
Tamarix chinensis	2.3636	1.8958	2.4664	− 0.2503	0.2480	0.5203	0.2224	0.4239	0.0000	0.7040	0.9054	0.9491	0.4133	5
Hedysarum scoparium	2.1347	1.3665	4.7356	0.3436	− 0.3226	− 0.0822	0.1607	0.2066	0.6878	1.0000	0.5230	0.5402	0.4407	4
Elaeagnus angustifolia	1.5386	0.8630	2.4808	− 0.3730	0.0335	0.2452	0.0000	0.0000	0.0044	0.6427	0.7616	0.7624	0.2225	9
Caryopteris mongholica	1.7574	1.4006	2.5960	0.0460	− 0.3572	− 0.0290	0.0590	0.2206	0.0393	0.8516	0.4999	0.5763	0.2807	8
Sabina vulgaris	2.0157	3.2996	4.5621	− 0.4719	− 0.4117	− 0.8784	0.1286	1.0000	0.6352	0.5935	0.4633	0.0000	0.4752	3
Amorpha fruticosa	3.4645	1.7662	3.8878	− 0.1139	0.1527	− 0.6727	0.5192	0.3707	0.4308	0.7720	0.8415	0.1395	0.5139	2
Ammopiptanthus mongolicus	1.7080	1.6452	3.1189	0.2106	0.3171	0.5954	0.0457	0.3210	0.1978	0.9337	0.9516	1.0000	0.4105	6
Weight index							0.3202	0.1976	0.1692	0.1406	0.0981	0.0743		

to also be resistant to dust, and even under irrigation in highly polluted areas, drought-resistant species may have poor growth. How to find suitable species is a major issue faced by local governments in vegetation restoration and environmental protection in coal mining areas.

The results of this study confirmed the third hypothesis: tree species with moderate drought resistance are also more resistant to air pollution. Drought resistant species should be planted in environments with light dust in coal mining areas; those with better dust resistance could be selected for sites with severe pollution and irrigation, and those with good drought resistance and dust resistance could be planted in areas with high pollution and water shortages. This study was not only the first time to select tree species with strong drought and dust resistance in coal mining areas, but also had wide applications in semi-arid areas of China. In addition, different indices of tree species under different growth conditions (high dust, drought, irrigation and non-irrigation), were discussed and which has important value for multi-objective tree species selection under complex growth environments. Although this study was completed under the polluted conditions of arid coal mining, it also has application value for the selection of tree species under polluted environments of other mining areas with the same aridity. Therefore, this study provides scientific basis for tree species selection in vegetation restoration of coal bases in arid and semi-arid environments across the world.

Conclusions

According to the results of this study, the following conclusions may be made: (1) Water consumption, relative leaf water content, relative water deficient, conductivity, and the levels of superoxidase and peroxidase had a relatively larger weights (> 0.05) and could be used as indices for the evaluation index system of drought resistance. (2) Dust retention per unit leaf area and per unit leaf weight, stomatal conductance, main root system length, transpiration and photosynthetic rates, harm index, water use efficiency, and root: shoot biomass ratios had a relatively high weight (> 0.05) and could be used as the indices to evaluate dust resistance of tree species. The order was *Caragana korshinskii* > *Amorpha fruticosa* > *Sabina vulgaris* > *Hedysarum scoparium* > *Tamarix chinensis* > *Ammopiptanthus mongolicus* > *Ulmus pumila* > *Caryopteris mongholica* > *Elaeagnus angustifolia*. (3) Shoot length (dust retention), stomatal conductance (dust retention), crown breadth (dust retention), peroxidase content (drought resistance), stem biomass ratio (dust retention), transpiration rate (drought resistance), superoxide dismutase content (drought resistance), dust retention per unit weight (dust retention), photosynthetic rate (dust retention),

Table 10 Comparison of the order of dust resistant and comprehensive drought and dust resistant for nine tree species

	1	2	3	4	5	6	7	8	9
Dust resistance	*Caragana korshinskii*	*Amorpha fruticosa*	*Sabina vulgaris*	*Hedysarum scoparium*	*Tamarix chinensis*	*Ammopiptanthus mongolicus*	*Ulmus pumila*	*Caryopteris mongholi*	*Elaeagnus angustifolia*
Drought and dust resistance	*Caragana korshinskii*	*Ulmus pumila*	*Amorpha fruticosa*	*Sabina vulgaris*	*Caryopteris mongholi*	*Ammopiptanthus mongolicus*	*Hedysarum scoparium*	*Tamarix chinensis*	*Elaeagnus angustifolia*

water consumption (drought resistance), malondialdehyde content (drought resistance), intercellular CO_2 concentration (drought resistance), catalase content (drought resistance), and survival rate (drought resistance) had a relatively large weight (> 0.03) and could be used as the indices for the comprehensive index system of drought resistance and dust resistance. The order was *Caragana korshinskii* > *Ulmus pumila* > *Amorpha fruticose* > *Sabina vulgaris* > *Caryopteris mongholica* > *Ammopiptanthus mongolicus* > *Hedysarum scoparium* > *Tamarix chinensis* > *Elaeagnus angustifolia*.

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