Germplasm Resources and Distribution of Oaks in China

Subjects: Plant Sciences

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Oaks (*Quercus* spp.) are a major component of subtropical and temperate forests in the Northern Hemisphere. There are approximately 464 species, and they are dominant tree species in ecosystems. Oaks have a long history of cultivation in Europe, North America, and other continents. They are also cultivated and distributed in most provinces of China.

oak trees germplasm resources distribution in China

1. Germplasm Resources of Oaks

1.1. Indigenous Oak Species in China

There are 450–500 species of oaks (*Quercus* spp.) in the world. Due to their high adaptability to different climatic and soil conditions, oaks are widely distributed in Asia, Europe, North America, and Africa, in the northern hemisphere. Previous studies have reported 66 species of oak trees in China, including 51 species, 14 varieties, and one forma. A more detailed literature review confirmed that there are 67 lineages of *Quercus* in China, including 52 species, 14 varieties, and one forma [1]. After deleting the unaccepted species names or reduplicated synonyms, there are 60 lineages of *Quercus* in China, including 49 species, 7 varieties, and 4 subgenera. (**Table 1**). Although previous reports categorized *Q. palustris* and *Q. robur* as indigenous oak species in China, other studies have shown that these two species were introduced to China from North America in the early 20th century [2]. Until now, *Q. palustris* and *Q. robur* have been considered foreign-introduced species in most studies, while some reports believe they were transplanted from the Shandong Province and Northeast China. However, no wild trees have been reported in these areas. Recent studies have also classified *Q. sichourensis* and *Q. edithiae* as being in the *Quercus* genus [3]. In North and Northeast China, there are *Q. wutaishanica*, *Q. mongolica*, *Q. dentata*, *Q. aliena* var. *acutiserrata*, *Q. aliena*, and *Q. variabilis*, among other species. These species provide critical habitats for oak silkworms, and approximately 70,000 tons of tussah cocoons are produced each year. In the Henan and Shandong Province, *Q. acutissima*, *Q. variabilis*, *Q. aliena* var. *acutiserrata*, and *Q. chenii* are the main species of oak, with 50,000 tons of tussah cocoons produced each year. In the Southwest of China, including Guizhou, Sichuan, and Shanxi Province, *Q. acutissima*, *Q. variabilis*, *Q. wutaishanica*, and *Q. fabri* are distributed, and approximately 50,000 tons of tussah cocoons are produced annually [4][5].

1.2. Imported Oak Tree Species

Although oaks are abundant in China, as a major forest tree species and urban greening species, they have not been extensively studied. In China, the number of tree species available for urban landscaping is quite low. To expand oak tree populations and utilize their resources effectively, China introduced oak trees as greening tree species. The oak trees were imported from Europe and America in the mid-19th century, through foreign missionaries, businessmen, and students [6]. However, oak trees were not systematically introduced or studied in China until in the 1960s, when the Chinese Academy of Forestry introduced more than 10 species of *Quercus* from the United States [7]. This provided abundant materials for the germplasm breeding improvement of oaks in China. Some companies and scientific research institutions have also conducted studies on species introduction. To date, approximately 35 species of *Quercus* have been imported from Europe and America (**Table 1**). The successful species introduction, domestication, and biological and ecological evaluation of these foreign oaks have been studied [8]. Many of them have been successfully domesticated; for example, *Q. texana* shows good tolerance to waterlogging, and *Q. virginiana* shows high tolerance to drought, salinity, and heavy metal stress [9]. These species have great potential for applications in coastal protection and mining area greening. Meanwhile, several foreign-introduced oaks (e.g., *Q. cinerea* also named *Q. incana*, *Q. cuneata*, and *Q. fraineitto*) were not suitable for the local climate [10].

Table 1. Germplasm resources of oaks in China.

No.	Species Name	No.	Species Name
1	*Quercus acrodonta* Seemen	49	*Quercus yiwuensis* Huang
2	*Quercus acutissima* Carruth.	50	*Quercus yunnanensis* Franch. (Formal name: *Quercus dentata* subsp. *yunnanensis* (Franch.) Menitsky)
3	*Quercus aliena* Blume	51	*Quercus acutissima* var. *septentrionalis* Liou (Formal name: *Quercus acutissima* subsp. *acutissima*)
4	*Quercus aquifolioides* Rehder. et E.H.Wilson.	52	*Quercus acutissima* var. *depressinucata* H.W.Jen et R.Q.Gao (Formal name: *Quercus acutissima* subsp. *acutissima*)
5	*Quercus baronii* Skan	53	*Quercus aliena* var. *pekingensis* Schottky
6	*Quercus bawanglingensis* Huang, Li et Xing	54	*Quercus aliena* var. *pekingensis* f. *jeholensis* (Liou et Li) H.Wei Jen et L.M.Wang (Formal name: *Quercus aliena* var. *pekingensis* Schottky)
7	*Quercus chenii* Nakai	55	*Quercus aliena* var. *acutiserrata* Maxim.
8	*Quercus cocciferoides* Hand.-Mazz.	56	*Quercus baronii* var. *capillata* (Kozlova) Liou

No.	Species Name	No.	Species Name
9	*Quercus dentata* Thunb.	57	*Quercus cocciferoides* var. *taliensis* (A.Camus) Y.C.Hsu et H.Wei Jen
	Quercus dolicholepis A. Camus	58	*Quercus mongolica* var. *crispula* (Blume) H.Ohashi
10	*Quercus dolicholepis* var. *elliptica* Y. C. Hsu et H. W. Jen (Formal name: *Quercus dolicholepis* A. Camus)	59	*Quercus mongolica* var. *mongolica*
11	*Quercus edithiae* Skan		*Quercus serrata* Murray
12	*Quercus engleriana* Seem.		*Quercus glandulifera* var. *stellatopilosa* W.H.Zhang (Formal name: *Quercus serrata* Murray)
13	*Quercus fabri* Hance	59	*Quercus serrata* var. *brevipetiolata* (A.DC.) Nakai (Formal name: *Quercus serrata* Murray)
14	*Quercus* × *fangshanensis* Liou		*Quercus serrata* var. *tomentosa* (B.C.Ding et T.B.Chao) Y.C.Hsu et H.Wei Jen (Formal name: *Quercus serrata* Murray)
15	*Quercus* × *fenchengensis* H. W. Jen et L. M. Wang	60	*Quercus senescens* var. *muliensis* (Hu) Y.C.Hsu et H.Wei Jen
16	*Quercus franchetii* Skan	61	*Quercus palustris* Münchh. [6]
17	*Quercus fimbriata* Y.C.Hsu et H.Wei Jen	62	*Quercus robur* L. [7]
18	*Quercus gilliana* Rehder. et E.H.Wilson.	63	*Quercus suber* L. [2]
19	*Quercus griffithii* Hook. f. et Thomson ex Miq.	64	*Quercus texana* Buckley [6]
20	*Quercus guyavifolia* H. Lév.	65	*Quercus shumardii* Buckley [10]
21	*Quercus* × *hopeiensis* Liou	66	*Quercus nigra* L. [9][11]
22	*Quercus kingiana* Craib	67	*Quercus phellos* L. [6][7]
23	*Quercus kongshanensis* Y.C.Hsu et H.W.Jen	68	*Quercus virginiana* Mill. [6][10]
24	*Quercus lanceolata* M.Martens et Galeotti ex A.DC.	69	*Quercus coccinea* Münchh. [7]
25	*Quercus lodicosa* O.E.Warb. et E.F.Warb.	70	*Quercus rubra* L. [7]
26	*Quercus longispica* (Hand.-Mazz.) A.Camus	71	*Quercus falcata* Michx. [6]

No.	Species Name	No.	Species Name
27	*Quercus malacotricha* A.Camus	72	*Quercus petraea* subsp. *Petraea* [6]
28	*Quercus marlipoensis* Hu et W.C.Cheng	73	*Quercus velutina* Lam. [7][11]
29	*Quercus mongolica* Fisch. ex Ledeb.	74	*Quercus stellata* Wangenh. [11]
30	*Quercus* × *mongolicodentata* Nakai	75	*Quercus macrocarpa* Michx. [11]
31	*Quercus monimotricha* Hand.-Mazz.	76	*Quercus alba* L. [11]
32	*Quercus monnula* Y.C.Hsu et H.Wei Jen	77	*Quercus laurifolia* Michx. [9]
33	*Quercus oxyphylla* (E.H.Wilson) Hand.-Mazz.	78	*Quercus* × *schuettei* Trel. [12]
34	*Quercus pannosa* Hand.-Mazz.	79	*Quercus michauxii* Nutt. [12]
35	*Quercus phillyraeoides* A. Gray	80	*Quercus lyrata* Walter [12]
36	*Quercus pseudosemecarpifolia* A. Camus	81	*Quercus ithaburensis* subsp. *macrolepis* (Kotschy) Hedge et Yalt. [13]
37	*Quercus rehderiana* Hand.-Mazz.	82	*Quercus bicolor* Willd. [14]
38	*Quercus semecarpifolia* Sm.	83	*Quercus cerris* L. [14]
39	*Quercus senescens* Hand.-Mazz.	84	*Quercus ellipsoidalis* E.J.Hill. [14]
40	*Quercus setulosa* Hickel et A.Camus	85	*Quercus gambellii* [14]
41	*Quercus sichourensis* (Y.C.Hsu) C.C.Huang et Y.T.Chang	86	*Quercus glauca* [14]
42	*Quercus spinosa* David	87	*Quercus imbricaria* [14]
43	*Quercus tungmaiensis* Y.T.Chang	88	*Quercus libani* [14]
44	*Quercus dentata* subsp. *stewardii* (Rehder) A.Camus	89	*Quercus muehlenbergii* [14]
45	*Quercus tarokoensis* Hayata	90	*Quercus petaea* [14]
46	*Quercus utilis* Hu et Cheng	91	*Quercus prinus* L. [14]
	Quercus variabilis Blume	92	*Quercus salicina* Blume [14]
47	*Quercus variabilis* var. *pyramidalis* T.B.Chao, Z.I.Chang et W.C.Li (Formal name: *Quercus variabilis* Blume)	93	*Quercus velutina* [14]

China, the United States, Russia, and India. Fossils of oaks are also widely distributed throughout geological history, and they are a dominant plant group in strata in the Northern Hemisphere from the Eocene epoch [15]. Archaeological data indicate that oaks were already widely distributed in China in ancient times. The Eocene-epoch *Q. rhombifolia* fossil found in Fushun, Liaoning Province, is the earliest fossil record of oak tree leaves in China. *Quercus* sect.

No.	Species Name	No.	Species Name
48	*Quercus wutaishanica* Mayr	94	*Quercus stellata* var. *margaretta* [14]

Note: 1–60 represent the native oak tree species in China; 61–94 represent the oak tree species introduced from abroad. The species names in former studies are modified as accepted names.

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dominant species, and their fossil record extends back to the Miocene. Early fossils of this sclerophyllous oak were found in Xigaze, the Tibet Autonomous Region (late Miocene), which was named *Quercus tibetensis* H. Xu, T. Su et Z.K. Zhou sp. nov. [16]. Other Sect. Brachylepides oak fossils were found in Xiaolongtan Basin, Yunnan province [17]. The earliest fossil of a deciduous oak was found in the Miocene epoch flora in Dunhua, Jilin province. This origin is later than that of the evergreen oaks. From archaeological research, the origin of *Quercus* may have been in the early stages of the Palaeocene, followed by accelerated species differentiation in the Eocene or Oligocene in East Asia, Europe, and North America. *Quercus praedelavayi* Xing Y.W. et Zhou Z.K. sp. nov. s from the upper Miocene was found in southwestern China [18]. *Quercus heqingensis* n. sp. from the late Pliocene was found in Heqing, Yunan province, China [19].

Deciduous broad-leaved tree species (especially *Quercus*) were dominant in vast regions of China. This was confirmed by archeological discoveries, including the 7000-year-old Xinle site in Shenyang, and the Chahai site in Fuxin County, Liaoning [20]. The analysis of charcoal fragments excavated from the Xiajiadian site (3500–4000 years ago) in Chifeng, Inner Mongolia, showed that the loess hills had a relatively warm and humid climate at the time, and that the zonal vegetation consisted of *Q. mongolica* and *Pinus tabulaeformis* forests [21]. Starch grains found on the surface of stone tools from the Shangzhai site (7000 years ago) in Pinggu, Beijing, show that the North China Plain was inhabited by deciduous broad-leaved zonal vegetation, consisting of oak species (such as *Q. mongolica*, *Q. aliena*, and *Q. acutissima*). The charcoal remains from the Beiqian site in Jimo, Shandong, showed that *Quercus* plants (especially *Q. acutissima*) have been the dominant species in the Jiaodong Peninsula since the Beixin cultural period (7000 years ago) [20].

2.2. Current Distribution of Oaks in China

Deciduous oaks are widely distributed in China, and form narrow belts in northern areas; in contrast, evergreen oaks are moderately distributed in southern China [22]. Deciduous oaks are dominant and constructive species (the main species in forest construction) in deciduous broad-leaved forests and mixed broadleaf-conifer forests in temperate zone and warm temperate regions, especially in North China. Their altitudinal distribution ranges from a few meters to 3500 m above sea level. China has three regions with concentrated distributions of oaks: (1) the Liaodong and Jiaodong peninsulas are hilly areas inhabited by deciduous oaks (mainly *Q. mongolica*, *Q. wutaishanica*, and *Q. acutissima*); (2) the Funiu and Dabie mountain areas show the highest diversity of *Quercus* species in China (18 species in total, including almost all species found in eastern, western, southern, and northern China); and (3) a wide range of mountainous areas in Sichuan, Yunnan, and Guizhou, which are inhabited by several unique species of oak trees (18 species known to date) [1] (**Figure 1**).

Figure 1. Oak distribution in China based on occurrence records obtained from the National Specimen Information Infrastructure database (www.nsii.org.cn, accessed on 23 December 2022). The different colors represent the collected plant specimen numbers (this reflects the abundance of *Quercus* samples in this area). Tree concentrated distributions in general areas are also shown in the picture.

The total oak forest area in China is 16.72 million hm^2, based on the 8th National Forest Resources Survey. Most of these are natural forests, and the area of oak trees is 16.1 million hm^2. The area of artificial oak forest is 0.61 million hm^2. The land area occupied by oak tree forests exceeds 100,000 hm^2 in 17 provincial regions, 500,000 hm^2 in 10 regions, and 1000,000 hm^2 in five regions (including Heilongjiang, Jilin, Liaoning, Hebei, and Inner Mongolia) [1]. Oak tree forests account for the highest proportion of dominant tree forests. The top ten tree species are oak, fir, larch, birch, poplar, masson pine, eucalyptus, spruce, Yunnan pine, and cypress, which account for 46.3% of the total forest area in China. There are about 20 species of deciduous oaks, being the main dominant species in temperate zones with broadleaved deciduous forest and mixed broadleaf-conifer forest. *Q. acutissima*, *Q. variabilis*, and *Q. dentata* are widely distributed in Northeast, Southeast, and Southern China. *Q. wutaishanica* and *Q. mongolica*, as representatives of deciduous oaks, are widely distributed in Northeast and North China and also located in Sichuan and Hubei provinces. In Yunnan Province, broadleaf oak timber reserves have reached 0.15 billion m^3, which represents 43% of broadleaf tree timber reserves. *Q. mongolica* is mostly distributed in Northeast China and east Inner Mongolia. There are 411,000 hm^2 oak forests in Jilin Province, which accounts for 7% of the local forest area. In Liaoning Province, oak forests account for 43.5% of the local forest area, which is 1.06 million hm^2. In Hebei Province, oak forests total 0.9 million hm^2 [23]. Based on the newest National Forest Resources Survey in 2019, *Q. mongolica* was the fifth most important tree (based on numbers), representing 8.294

billion trees and 0.583 billion m^3 timber reserves. *Q. wutaishanica*, in the thirteenth most important position, has 2.647 billion trees and 0.183 billion m^3 timber reserves.

3. Ecological Adaptability of Oak Trees

3.1. Morphological and Physiological Adaptability of Oaks

Oak trees vary in their leaf size and shape (**Figure 2**). This variation might reflect adaptations or plastic responses to different environments [24][25][26]. Leaf variation is influenced by genetic and environmental factors [27]. Oaks are deep-rooted plants. Their root systems are well-developed and deeply distributed, and the main roots of one-year-old trees can reach a soil depth of up to 100 cm [5]. In *Q. variabilis*, the main root length of young seedlings is 10 cm on the 58th day (no fibrous roots) and 50 cm on the 73rd day (with a large number of fibrous roots). The main roots of mature *Q. variabilis* can reach 6–7 m deep [1]. The well-developed root systems of oaks are important for soil and water conservation in mountainous areas. Roots also have varying degrees of plasticity, to adapt to environmental stress based on morphological or physiological plasticity and root chemical changes [28]. In addition, oak trees are obligate mycorrhizal symbionts. Their root hairs are 100–150 μm long and develop an ectomycorrhizal symbiosis with certain fungi. The mycelia of mycorrhizal fungi surround the root hair. They enter the cortex and invade the intercellular spaces. The mycelia extend outwards on the root surface in the form of villi and absorb water and nutrients from the soil, to maintain the growth of the oak [29]. Annual seedlings inoculated with mycorrhizal fungi can attain approximately double the biomass of control groups. For example, *Q. wutaishanica* inoculated with symbiotic fungi (such as *Comphidius viscidus* and *Russula foeten*) showed improved seedling growth, net photosynthetic rate, and total nitrogen and phosphorus contents [30]. Mycorrhizae affect the absorption of phosphorus fertilizers and have an antibiotic effect, thus protecting the roots of oaks from infestation by root rot fungi [1]. Mycelia can also secrete various types of extracellular enzymes that promote the decomposition of organic matter in the soil [31][32]. Based on these functions, mycorrhizal fungi can be used for the seedling culture and repopulation of oak trees.

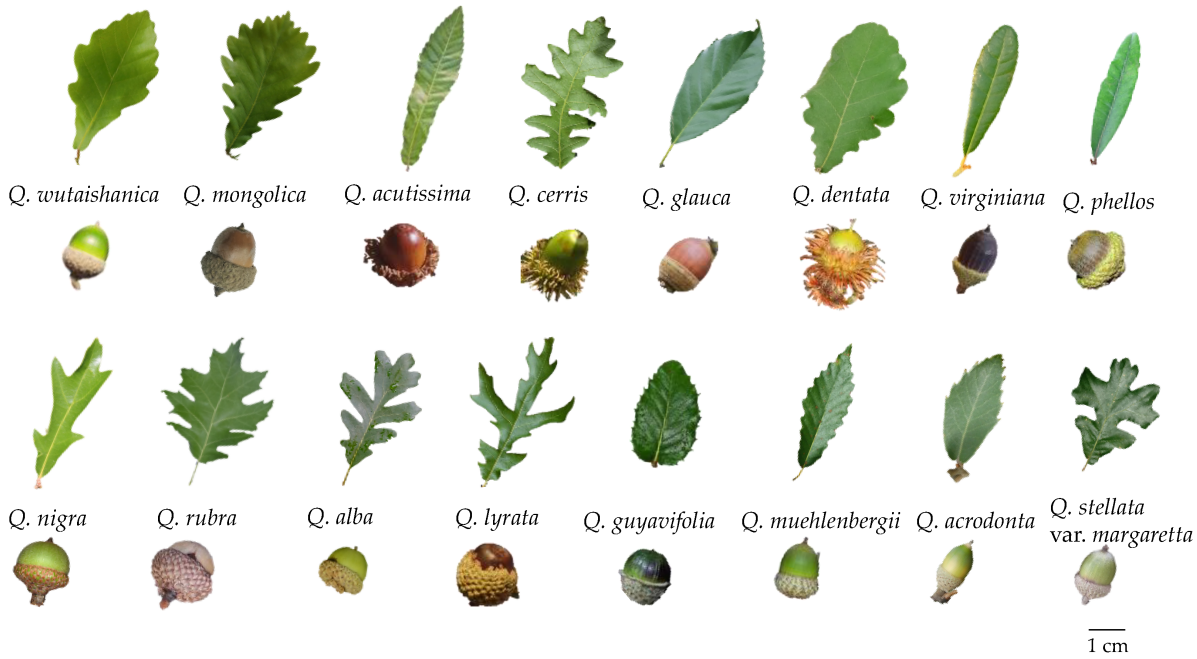

Figure 2. Morphology and diversity of leaves and acorns among a few oak species in China.

Most oaks are heliophilous or neutral species that do not have strict soil condition requirements for growth. They grow rapidly in moist, fertile, and well-drained neutral or slightly acidic sandy loam soil (particularly in ravines and foothills). They can also tolerate stress and soil infertility, because of their deep-rootedness and mycorrhizal formations. In addition, acorns have a strong sprouting ability, while trees are not transplantation-resistant. Oaks are adaptable to a wide range of temperatures. Deciduous species of oak trees (such as *Q. mongolica*, *Q. wutaishanica*, and *Q. dentata*) are quite cold-resistant, whereas evergreen species are relatively demanding, requiring warmer temperature conditions [33]. Deciduous species are also relatively drought-resistant, whereas evergreen species are moisture-loving. The drought-tolerant species of oaks indigenous to China include *Q. acutissima*, *Q. variabilis*, *Q. wutaishanica*, and *Q. mongolica*. Moisture-loving species in southern China include *Q. fabri*, *Q. serrata*, and *Q. chenii*. Most foreign-introduced species of oaks are hygrocolous and highly moisture-resistant. In general, oaks exhibit strong resistance to wind, fire, pollution, and smoke. Species such as *Q. variabilis*, *Q. acutissima*, *Q. wutaishanica*, *Q. suber*, and *Q. mongolica* have a thick bark and exhibit fire resistance, which makes them ideal fire-resistant tree species [34]. Owing to its resistance to smoke and poisonous gas, *Q. mongolica* is a dominant tree species in the greening and isolation belts of industrial and mining areas [35]. Some species of oaks also exhibit saline-alkaline tolerance, such as *Q. texana* and *Q. nigra* [36]. In addition, *Q. variabilis* can absorb and accumulate heavy metals in suburban areas [37].

3.2. Climate Change Influences

Oak is one of the most diverse and ecologically important trees in the Northern hemisphere. They exhibit high tolerance to different environments and have proved useful in evolutionary mechanism research [38][39]. Climate change effects the oak pollen season, especially the start dates and season lengths [40]. In the Mediterranean basin, *Q. pubescens*, as an downy oak, is often used for anti-drought research in morphoanatomy, physiology, and

genetic evolution. A significantly earlier senescence increased the sugar content in leaves, to maintain a higher photosynthetic potential [41]. Drought induced an increase in oxidative pressure from the transcript level [42]. Under a constant CO_2 concentration, the net primary production was positively affected by longer vegetation periods and negatively by respiration costs in European oak trees [43]. In the Mediterranean region, climate change induces heat waves and droughts, disturbing forest species and affecting productivity. The cork oak (*Q. suber*) is resilient and cork growth rapidly recovers when droughts finish [44]. Under long-term environmental changes, trees mainly rely on phenotypic changes. In two oaks, *Q. pyrenaica* (more tolerant to drought) and *Q. petraea* (less tolerant to drought), *Q. petraea* displayed a greater response to moisture availability, by triggering a tighter stomatal control across genetic groups [45].

Oaks comprise 13% of the natural forest in China. Studies specifically addressing oaks adaptation to climate change in China are needed. Greenhouse gases will affect the species geographical distribution and change the richness distribution pattern. Based on 35 oak species and data of 19 bioclimatic variables in China, the *Quercus* distribution will migrate to high altitudes or high latitudes, from being primarily distributed in the area of southwestern China. A high percentage of species loss will happen in mountainous areas, while other regions will gain species due to a northward shift in the years 2050 and 2070 [46].

4. Threats to Oak Trees

There are several diseases that can influence oak trees, including leaf, trunk, root, and acorn diseases. Leaf diseases are the most common, and most pathogens are fungi. The infected leaves exhibit growth deficiencies and death. Powdery mildew [47], brown leaf spot, rust disease, and “frog eye” disease mainly affect healthy leaves [48] (**Figure 3**). White rot disease is found in the trunk and roots.

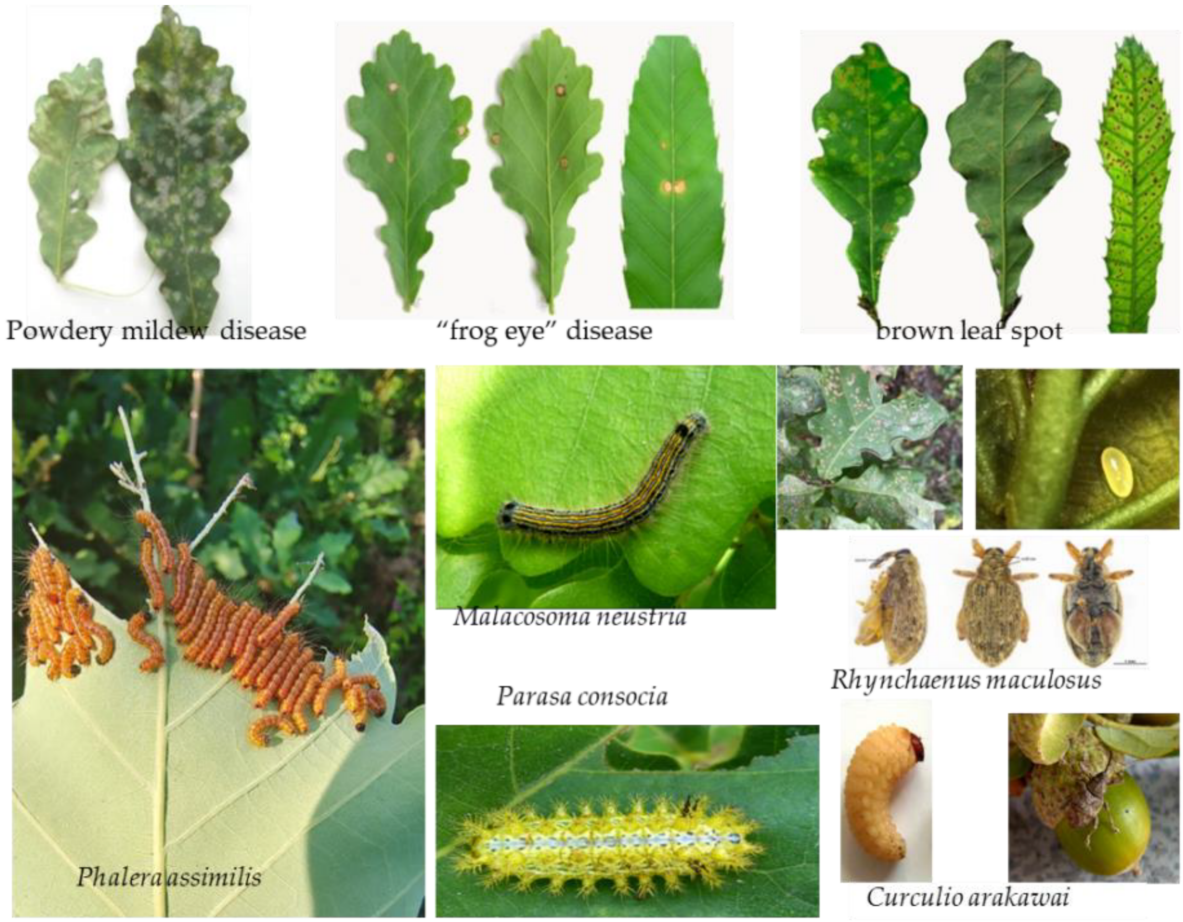

Figure 3. Partial leaf diseases and oak tree pests.

There were 624 kinds of pests reported in 2010 as damaging the leaves, trunks, and acorns in oak trees [49]. Regarding leaf pests, *Malacosoma neustria*, *Camptoloma interiorata*, *Parasa consocia*, *Phalera assimilis*, *Phalerodonta albibasis*, and *Fentonia ocypete* greatly impact leaf growth. In recent years, an emerging oak pest, *Rhynchaenus maculosus*, has caused spectacular damage in Jilin, Heilongjiang, and Liaoning Province. This pest had no reports till 2012 from when it was first recorded as a new species in China in 1987. It can induce leaf damage symptoms, including blister-like blotches on leaf margins. This pest is an univoltine insect and overwinters as an adult in the leaf litter. Both the larvae and adults can influence leaf growth. The leaf damage in Liaoning province increased from 6.9% in 2016 to 15.4% in 2018 [50][51]. Common trunk and acorn pests include *Mallambyx raddei*, *Laspeyresia splendana*, and *Curculio arakawai* (**Figure 3**).

Other than disease, the illegal timber trade and harvesting for charcoal also threaten oak resources. Deforestation for farming and increasing mountain fires influence oak growth. For example, *Quercus variabilis* bark is widely used for cork production. Based on the red list statistics, these are 32 critically endangered species and 57 endangered species of *Quercus* (https://www.iucnredlist.org/) (accessed on 27 November 2022). In China, there are 12 species of oak trees whose numbers are decreasing, including *Q. chenii*, *Q. edithiae*, *Q. fimbriata*, *Q. kingiana*, *Q. lodicosa*, *Q. marlipoensis*, *Q. mongolica*, *Q. sichourensis*, *Q. utilis*, *Q. macrocarpa*, *Q. alba*, and *Q. libani*. Two of them, *Q. fimbriata* and *Q. marlipoensis*, are listed as critically endangered species. Four of these, *Q. edithiae*, *Q. kingiana*,

Q. lodicosa, and *Q. utilis*, are listed as endangered species (https://www.iucnredlist.org/) (accessed on 27 November 2022).

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