New record and prediction of the potential distribution of the invasive alien species Brassica tournefortii (Brassicaceae) in Korea

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ABSTRACT: The invasive alien species Brassica tournefortii Gouan (Brassicaceae) is herein reported for the first time in Korea, from Gunsan-si, Gochang-gun, and Jeju-si. Brassica tournefortii can easily be distinguished from B. juncea and B. napus by its dense stiff hairs at the base of the stem and leaves, basally and distally branched stems, partially dehiscent fruits, and seeds that become mucilaginous in the presence of moisture. Although some taxonomists have classified this species as belonging to Coincya Rouy based on its fruit and seed characteristics, the existence of one vein on the fruit valves and our maximum likelihood analysis using internal transcribed spacer sequences placed it in Brassica. Distribution data, photographs, and a description of B. tournefortii are presented herein. Moreover, potential changes in the distribution of B. tournefortii were predicted under different climate scenarios, but our analysis showed that the probability of the spreading of this species is low. Nevertheless, continuous monitoring is necessary for an accurate assessment. The results of the present study can be used to conduct an invasion risk assessment and can assist with the effective management of this invasive alien species.

Keywords: Brassica, Brassica tournefortii, internal transcribed spacer, invasive plant, new record, species distribution model

INTRODUCTION

Brassicaceae Burnett comprises 351 genera and 4,000 species worldwide, mostly distributed across the temperate regions of the northern and southern hemispheres (Abdelhameed et al., 2020). The family generally has typical morphological characteristics: tetradynamous stamens, four cruciform or butterfly-like petals, and capsules with two locules divided by septa (Beilstein et al., 2006).

Brassicaceae members having conduplicate cotyledons and the presence or absence of simple hairs are classified into tribe Brassiceae, and some of those with dehiscent fruits at maturity are further subdivided into subtribe Brassicinae (Kadereit, 1994). Meanwhile, most members of Brassica have completely dehiscent fruits at maturity, whereas some plants with partially dehiscent fruits can even be classified as Coincya Rouy (Leadlay and Heywood, 1990; Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Nagpal et al., 2008; Al-Shehbaz, 2012). Owing to the highly variable morphological characters, however, taxonomy of some taxa within Brassica is debatable. Therefore, comprehensive studies for both morphology and molecular patterns are required to elucidate the taxonomic delimitations of some taxa.

In the present study, we report the invasive alien species Brassica tournefortii Gouan for the first time in South Korea. It was first detected in Gunsan-si of Jeollabuk-do in 2018, after which it was also found in Gochang-gun of Jeollabuk-do and Jeju-si of Jeju-do in 2020 (Fig. 1). Moreover, this plant has been treated as either B. tournefortii or Coincya tournefortii (Gouan) Alcaraz, T. E. Díaz, Rivas Mart. & Sánchez-Gómez (Alcaraz Ariza et al., 1989; The Plant List, 2013; POWO, 2022). Hence, its taxonomic position was
reviewed by comparing its morphological characteristics with those of related species in South Korea and by using nuclear ribosomal DNA internal transcribed spacer (ITS) sequence data—which is a useful marker for phylogenetic analysis of the Brassicaceae (Álvarez and Wendel, 2003; Qi et al., 2007; Warwick et al., 2010; Salariento et al., 2013)—obtained from collected materials in Gochang-gun and registered in the National Center for Biotechnology Information (NCBI) database.

The species’ potential distribution under climate change scenarios was also modeled based on the current species distribution information (GPS data) in Gunsan-si, Gochang-gun, and Jeju-si. Invasive alien plant tend to have high dispersal abilities, rapid growth with short generation times, and high tolerance of broad environmental conditions. Therefore, climate-related changes will almost certainly lead to changes in the distribution of alien plant species, as their populations respond to variability and changes in temperature, precipitation, and biotic interactions. Predicting how invasive species will respond under potential climate change scenarios is difficult but understanding alien plant species’ current and future distribution patterns under different climate scenarios may provide primary data that can be used for invasion risk assessment (Moran and Alexander, 2014).

The findings of the present study elucidate the identification of Brassica in South Korea, besides providing data on the distribution of B. tournefortii, which can be a fundamental resource for the invasion risk assessment and effective management of this alien plant species.

**MATERIALS AND METHODS**

**Morphological analysis**

Living, dry, and immersed specimens collected in 2018–2021 from Gunsan-si and Gochang-gun of Jeollabuk-do and Jeju-si of Jeju-do island were studied. Morphological features were analyzed under a digital camera (Nikon D810 + Nikon 105 mm AF Micro-Nikkor, Tokyo, Japan) and measured using a digital Vernier caliper (Mitutoyo 500-196-30 absolute digimatic Vernier caliper, Tokyo, Japan). The obtained results were compared with descriptions and illustrations of related genera and species from previous studies (Leadlay and Heywood, 1990; Kaderiet, 1994; Al-Shehbaz et al., 2006a, 2006b; Nagpal et al., 2008; Al-Shehbaz, 2012). The examined material has been deposited in the Korea National Arboretum (KH).

**Molecular genetic analysis**

**DNA extraction and PCR**

Three samples of fresh leaves of B. tournefortii collected from Gochang-gun in 2021 were stored in silica gel and completely dried. A tissuelyser (Mixer Mill MM 200, Retsch, Haan, Germany) was used for pulverization, and total genomic DNA was extracted using the DNeasy Plant Mini Kit (Qiagen, Hilden, Germany). The PCR mix consisted of 1 µL of DNA (extracted using the AccuPower PCR PreMix; Bioneer, Daejeon, Korea) with 10 µmol of ITS1 (forward) and ITS4 (reverse) primers with 1 µL and 17 µL of distilled water, respectively. PCR was performed in a DNA thermal cycler (Biometa, Whatman Co., Göttinngen, Germany), with 35 cycles of 5 min at 94°C, 1 min at 94°C, 1 min at 54°C, and 1 min at 72°C, followed by 7 min at 72°C for fixation. PCR product purification and sequencing were performed by Macrogen, Co., Ltd. (Seoul, Korea).

**Phylogenetic analysis**

The ITS sequence data of B. tournefortii from Gochang-gun were compared with ITS sequences of related genera
and species obtained from the NCBI database. In total, 20 species of *Brassica* and four of *Coincya* were included. *Sisymbrium officinale* (L.) Scop. and *Barbarea orthoceras* Ledeb. were used as outgroups. The sequences were aligned using MAFFT in Geneious ver. 8.0.5 (https://www.geneious.com). Maximum likelihood (ML) analysis was performed using 5,000 bootstraps and the STR + R2 model in the IQ-TREE 1.6.8 software (http://www.iqtree.org).

**Potential distribution analysis**
To predict the projection and change of potential distribution according to the current and climate change scenarios of *B. tournefortii*, the distribution coordinates of each *B. tournefortii* individual were collected from Gochang-gun, Gunsan-si, and Jeju-si. For predictive analysis, the SSDM package was used in the RStudio program based on the collected distribution coordinates (Schmitt et al., 2017). The Ensemble Species Distribution Models (ESDMs) fits nine algorithms, explores the prediction range across different species distribution models (SDMs), and then finds consensus among the SDM predictions (Table 1). The 23 environmental factors most commonly applied were used (e.g., mean annual temperature and precipitation) (Table 2).

To determine the potential distribution of *B. tournefortii* in South Korea under future climate trajectories, we applied the 4.5 and 8.5 scenarios of the Representative Concentration Pathway (RCP) for three different periods (current, 2050, and 2070). The RCP 4.5 scenario, as presented in the 5th IPCC report, is a stabilization scenario in which the total radiative forcing reaches 4.5 W/m² by 2100 and stabilizes due to the employment of various technologies and strategies to reduce greenhouse gas emissions (IPCC, 2013).

By presenting only the potential distribution and the significantly correlated factors in our analysis according to the current and climate change scenarios, rather than comparing models, the focus was on predicting changes in the distribution of an alien species.

**RESULTS**

**Morphological analysis**
The basal leaves of young *Brassica tournefortii* have deep dissected lobes and are densely hirsute (Fig. 2B, F, G), closely resembling the radical leaves of young *Cirsium japonicum* Fisch. ex DC. var. *maackii* (Maxim.) Matsum. In addition, the flowering plant is similar to those of the species of genera *Sisymbrium* Burnett on *Raphanus* L. (Fig. 2B, I, J), but the characteristic of the fruit, i.e., dehiscence into two valves along the suture at maturity, confirms that the species belongs to *Brassica* (Fig. 2O) (Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Oh, 2007).

Apart from these features, *B. tournefortii* can also be easily distinguished from the two other *Brassica* species, *B. juncea* (L.) Czern. and *B. napus* L., by many branches basally and distally on the stem, hairs on proximal stems, remain seeds in indehisced fruit beak, seeds with mucilaginous seed coats in the presence of moisture (Fig. 2B, D, P, Q) (Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Oh, 2007).

**Molecular genetic analysis**
In total, 28 ITS sequences were obtained from two accessions of *B. tournefortii* and the 24 related taxa (with two outgroups: *Barbarea orthoceras* and *Sisymbrium officinale*) (Fig. 3). The total alignment length of the ITS was 580 base pairs, and 74 variable sites were found. The identical

| Statistical method | Description | Reference |
|--------------------|-------------|-----------|
| GAM                | General additive models | Wood (2006) |
| GLM                | Generalized linear models | R Core Team (2015) |
| MARS               | Multivariate adaptive regression splines | Milborrow (2016) |
| MAXENT             | Maximum entropy | Hijmans et al. (2016) |
| CTA                | Classification tree analysis | Therneau et al. (2015) |
| GBM                | Generalized boosted models | Ridgeway (2015) |
| ANN                | Artificial neural networks | Venables and Ripley (2002) |
| RF                 | Random forests | Liaw and Wiener (2002) |
| SVM                | Support vector machines | Meyer et al. (2015) |
sites were 340 base pairs (58.6%). The overall GC ratio was 53.5% for ITS.

In ML trees, all 26 accessions of *Brassica* and *Coincya* species formed a monophyletic group (bootstrap value; BS = 97), excluding the outgroups (Fig. 3). Members of *Brassica* were separated into two clades, one of which formed a cluster with *Coincya*, even though overall node support was not robust (BS = 51). The identity of the Gochang-gun individual was *B. tournefortii*, as strongly supported by BS (BS = 100).

**Potential distribution analysis**

The potential distribution of *Brassica tournefortii* in the current climate condition was predicted, including the coastal regions where the plants were recorded (Gunsan-si, Gochang-gun, and Jeju-si), covering 2.2% of the total area of South Korea (Fig. 4A). In the RCP 4.5 scenario, the distribution was projected to reduce to 2.2% by 2050 and to 1.6% by 2070 (Fig. 4B, C). In both cases, bio 14 (precipitation of the driest month) was assessed as a significant factor (Fig. 5B, C). In this scenario, compared to the result that predicted the current climate condition, the probability of distribution of *B. tournefortii* decreased in Gochang-gun and Jeju-si but increased on the islands of the Yellow Sea. However, in general, the area of potential distribution decreased with time. In the RCP 8.5 scenario, the potential distribution was projected to increase to 1.5% by 2050, with the contribution of bio 3 (isothermality), and to 1.9% by 2070, influenced by bio 14 (Figs. 4D, E, 5D, E). In this scenario, the probability of distribution of *B. tournefortii* decreased in Gunsan-si and Gochang-gun and then increased in Gunsan-si, Gochang-gun, and Jeju-si by 2070.

**DISCUSSION**

*Brassica tournefortii*, unlike other *Brassica* species in South Korea, has pinnatisect basal leaves that are densely hirsute. Thus, at young stages, it is sometimes confused with either *Sisymbrium* or *Raphanus* species (Fig. 2B, F, G).
However, they are very different in the presence of bracts on racemes, fruit shape, and cotyledon type of seeds (Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Oh, 2007). *B. tournefortii* and *Raphanus* species have racemes without bracts, globose seeds, and conduplicate cotyledons, whereas *Sisymbrium* species have racemes with bracts, flattened seeds, and incumbent cotyledons (Fig. 2B, P, Q) (Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Oh, 2007) (Fig. 2P, Q). Conversely, *B. tournefortii* can be distinguished from *Raphanus* species by morphological features such as yellow...
or light yellowish petals (vs. *Raphanus*, which has purple, pink, yellow, or white petals) and dehiscent fruits along the suture (vs. *Raphanus*, which has indehiscent fruits, often breaking transversely into segments fruits) (Fig. 2J, L, O) (Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Oh, 2007).

The two other *Brassica* species from South Korea, *B. juncea* and *B. napus*, have basal leaves that are not pinnatisect but lyrate to pinnatifid and are glabrous or sparsely hirsute; therefore, *B. tournefortii* can be easily distinguished from these two species. Moreover, both *B. juncea* and *B. napus* are branched at the upper part of the stem, have completely dehiscent fruits at maturity, with seed coats that do not turn mucilaginous when in contact with water, but *B. tournefortii* has stems branched basally and distally, partly indehiscent fruit beaks, and seed coats that become mucilaginous with moisture (Fig. 2B, D, P, Q) (Al-Shehbaz et al., 2006a, 2006b; Oh, 2007).

Meanwhile, one Brassicaceae member, the genus *Coincya*, shares a typical trait of partly indehiscent fruits; thus, some taxonomists consider this species as belonging to *Coincya* (Leadlay and Heywood, 1990; Kadereit, 1994; Al-Shehbaz et al., 2006a, 2006b; Nagpal et al., 2008; Al-Shehbaz, 2012). However, the existence of one vein on the fruit valves reveals that *B. tournefortii* really belongs to *Brassica*, as *Coincya* has three or more veins (Leadlay and Heywood, 1990; Al-Shehbaz et al., 2006a) (Fig. 2O). Furthermore, our ML tree showed that *Coincya* is not monophyletic because it clusters with the other group of *Brassica*, and *B. tournefortii* is more closely related to *Brassica* than to *Coincya* (Fig. 3). Therefore, we herein classify it as a *Brassica* member.

*Brassica tournefortii* is native to North Africa and countries near the Caribbean Sea, Central Asia, and Western India (Malusa et al., 2003; Dahlin et al., 2012; Abd El-Gawad, 2014; Curtis and Bradley, 2015; Winkler et al., 2019). The species was mainly known to have naturalized and spread to Australia and southern parts of the U.S.A. (Trader et al., 2006; Barrows et al., 2009; Dahlin et al., 2012; Abd El-Gawad, 2014; VanTassel et al., 2014). It was recently reported to have been introduced into China and Japan (Curtis and Bradley, 2015; Winkler et al., 2019; Kraus et al., 2020). In the U.S.A., *B. tournefortii* is presumed to have been introduced through date palm import from the Middle East in 1927 (Sánchez-Flores, 2007; Marushia et al., 2012; Winkler et al., 2019).

*Brassica tournefortii* usually grows on coastlines and along roads and railways (Trader et al., 2006; Lillian, 2017; Rahmani et al., 2020). As it shows strong resistance to drought stress, a desert ecosystem is suitable for its growth (Choudhary and Joshi, 2001; Abd El-Gawad, 2014; Winkler et al., 2018; Rahmani et al., 2020). The lifecycle of *B. tournefortii* is short, with two to three generations within a year; it produces thousands of seeds at a time, which is advantageous for dispersion; and the seeds have a high rate of germination. These factors make this species highly invasive (Bangle et al., 2008; Dahlin et al., 2012; Abd El-Gawad, 2014; Curtis and Bradley, 2015). *B. tournefortii* seeds can remain dormant in an environment unfavorable for germination, and they can withstand flooding as the seed coats become mucilaginous when supplied with excessive moisture (Sánchez-Flores, 2007; Bangle et al., 2008; Dahlin 2012).

**Fig. 3.** Maximum likelihood (ML) tree of internal transcribed spacer sequence data of *Brassica tournefortii* Gouan and related species. Numbers above branches indicate bootstrap support values.
et al., 2012; Abd El-Gawad, 2014; Berry et al., 2014; Curtis and Bradley, 2015). These mechanisms also allow the seeds to adhere to animals, further facilitating dispersion (Li et al., 2015; Winkler et al., 2018, 2019).

The spread of *B. tournefortii* is considered a chief factor in the reduction of biodiversity in desert ecosystems. In desert regions in the south of the U.S.A., the increase in annual precipitation and transport infrastructure has increased the spread of *B. tournefortii* as compared to the early distribution regions of the species (Malusa et al., 2003; Schiermeier, 2005; Barrows et al., 2009; Marushia, 2009; Dahlin et al., 2012; Marushia et al., 2012; VanTassel et al., 2014; Winkler et al., 2019), which in turn has caused it to monopolize resources previously used by native plants and disturb the habitats of small animals such as lizards (Trader et al., 2006; Sánchez-Flores, 2007; Bangle et al., 2008; Dahlin et al., 2012; Abd El-Gawad, 2014; Berry et al., 2014; Curtis and Bradley, 2015; Rahmani et al., 2020). The spread of this invasive alien plant was found to have also influenced the frequency of fires in the desert (Steers, 2008), prompting studies worldwide to identify the growth, ecological, and physiological characteristics of the species to control its dispersion and invasion (Chauhan et al., 2006; Trader et al., 2006; Marushia, 2009; Abd El-Gawad, 2014; Alfaro and Marshall, 2019). In particular, notable efforts have been made in the U.S.A., where *B. tournefortii* was designated as an invasive alien plant to prevent its spread and damage (Chauhan et al., 2006; Lillian, 2017; Kraus et al., 2020).

*Brassica tournefortii*, which inhabits in arid and semi-arid areas, showed narrow range of potential distribution according to the current environmental envelope in South Korea, and it was evaluated that the potential distribution area shown to not increase under the climate change scenarios (Fig. 4). However, the studies of Winkler et al. (2018, 2019)

![Fig. 4. Potential distribution of Brassica tournefortii Gouan under the current scenario and climate change scenarios.](image_url)

A. Present. B. RCP4.5 2050. C. RCP4.5 2070. D. RCP8.5 2050. E. RCP8.5 2070.
revealed that *B. tournefortii* exhibits population variability in germination and growth according to the local seasonal precipitation. Therefore, it is assumed that this species can adopt to traits of local environment, and increasing reproduction and competitiveness with native species. In Korea, ecological studies have not been conducted to date on *B. tournefortii* in the three aforementioned regions under human interference and specific environmental conditions (e.g., nutrient distribution; seed production; vegetation; competing species; soil; and the biological interaction network, including herbivores). Instead, considering the studies on the species’ dispersion in the U.S.A. and its growth and ecological characteristics, the probability of rapid spread in South Korea can be regarded as extremely low due to the lack of a broad prairie or desert area. The potential distribution of *B. tournefortii* was assessed that this species’ dispersion depends on spring and autumn precipitation, with little increase predicted for the concerned regions (Figs. 4, 5).

It is assumed that these results arise from *B. tournefortii* recent introduction to Korea (first detection in Gunsan-si in 2018) and main distribution along the coast. However, recently introduced alien plants ensure sustainability by forming a soil seed bank in a given region and spreading to surrounding regions, and these may be supported by macroscale climate factors and complex interactions in the ecosystem (Lim et al., 2020; Park and Choi, 2020). Under low conditions of inter- and intra-specific resource competition, *B. tournefortii* produces a high amount of seeds (Trader et al., 2006). The species’ characteristic onset in early spring, when no other species are growing, may enable the
dispersion of *B. tournefortii* from the site of introduction in South Korea. This survival strategy of *B. tournefortii* may enable a continued invasion in future climate change scenarios through self-fertilization and propagation, and it is expected to compete with native species. In addition, future spread to island and coastal regions, cultivated lands, disturbance zones with sand-rich soil, and agricultural lands with environments similar to the current habitats is possible. Thus, preparation against the uncontrolled spread of the species, especially under anthropogenic pressure, is necessary. A possible measure for preventing the species’ migration toward inland regions is the removal of *B. tournefortii* plants along sand bed channels and dry lands at banks.

SDM analysis using distribution information of recently introduced alien plants revealed narrow predicted areas because a narrow environmental factor distribution range was used. Although the approach according to the current conditions and climate change scenarios has these limitations, it clearly has the advantage of rationally extracting uncertain conditions and climate change scenarios has these limitations, used. Although the approach according to the current

**Taxonomic treatment**

*Brassica tournefortii* Gouan, Ill. Observ. Bot. 44, t. 20A, 1773; *Erucastrum tournefortii* (Gouan) Link, Handbuch 2: 317, 1831; *Coincya tournefortii* (Gouan) Alcaraz, T.E. Diaz, Rivas Mart. & Sánchez-Gómez, Itinera Geobot. 2: 108, 1989. (Fig. 2)

Herbs annual, erect, 0.1–1 m tall. Stems branched basally and distally, green or purple, hirsute proximally. Basal leaves rosettes, persistent; petiole 1.0–4.0 cm; blades lyrate, deeply pinnatisect, 11.0–20.0 × 4.0–6.0 cm, with lobes 4–8 each side, margin serrate to dentate, hirsute; terminal leaflets 2.0–3.2 × 2.0–2.5 cm; lateral leaflets 2.0–3.0 × 1.0–2.0 cm. Cauline leaves alternate, sub sessile or petiolate; petiole less than 2.0 cm; blades oblanceolate, 3.0–5.0 × 2.0–3.0 cm, margins serrate, base taper ed, not auriculate or amplexicaul, reduced in size distally and densely hirsute. Inflorescence raceme, elongate rachis with flowering. Flowers bisexual, actinomorphic; pedicel 3.6–4.5 cm long; sepals 4, erect or spread, elliptic, central sepals 3.6–3.8 × 1.4–1.5 mm, lateral sepals 3.1–3.7 × 1.1–1.3 mm, apex obtuse, base saccate, exterior usually purplish, 1–2 bristles on upper; petals 4, oblanceolate or spatulate, 5.5–7.0 × 1.5–2.0 mm wide, apex round or obtuse, light yellow with dark yellow or brown veins on surface; stamens 6,

tetradynamous, linear, white; central filaments 2.5–3.3 mm long, lateral filaments 1.0–1.6 mm long; anthers oblong, yellow, ones of central filament 1.4–1.6 × 0.6–0.8 mm, ones of lateral filaments 1.2–1.4 × 0.5–0.7 mm; nectary glands 4, median glands 2, lateral glands 2; pistil 2.9–3.3 × 0.6–0.8 mm, 2-locculed; ovules 5–8 per locule; styles 1.3–1.7 mm long; stigma capitate, 0.5–0.7 mm wide. Fruit capsule, dehiscent, spreading or ascending, torulose, cylindric, 4.5–6.0 cm long, 2.1–2.5 wide; valves 2 with a prominent midvein; terminal segment 1–3-seeded, indehiscent; stalk 7.7–15.8 mm long. Seeds uniseriate, globose, light reddish brown to black, 2.1–2.5 mm diam; seed coat reticulate, mucilaginous when wetted; cotyledons con duplicate.

**Korean name:** Sa-mak-gat (사막갓)

**English name:** Sahara mustard, African mustard.

**Flowering:** February–April, Fruiting: April–May.

**Distribution:** North Africa, countries near the Caribbean Sea, Central Asia, Western India, Australia, and south-western regions of the U.S.A., China, Japan, and Korea.

**Distribution in South Korea:** Gunsan-si, Gochang-gun, Jeju-si.

**Examined specimen:** GREECE. Chalkidiki: Flojita, 11 Apr 2003, B 10 0123089 (B); N Nea Moudania, 15 May 2019, B 10 1081147, B 10 1081148 (B). KOREA. Jeollabuk-do: Gunsan-si, Osikdo-dong, 13 May 2018, NMJ201805131, NMJ201805132, NMJ201805133 (KH); Gochang-gun, Jaryong-ri, 21 Mar 2021, KJS0708 (KH). Jeju-do: Jeju-si, Iho l-dong, 13 Mar 2021, LSG0006 (KH); 21 Apr 2021, KES2104211, KES2104221 (KH). U.S.A. California: Riverside, 9 Mar 1995, 00043448 (NY). Nevada: Clark, 3 Apr 1998, 03173361 (NY). Utah: Washington, 11 Jan 1999, 00404781 (NY). Arizona: Mohave, 8 Apr 2000, 00584551 (NY).

**A key to genera and species related to *Brassica* L. in Korea**

1. Racemes bracteate; seed flattened; cotyledons incumbent

                    .. *Sisymbrium* Burnett (노랑장대속)

2. Petals purple, pink, yellow or white; fruits indehiscent, often breaking transversely into segments

                       .. *Raphanus* L. (무속)

3. Vein of fruit valves more than 3

                .. *Coincya* Rouy

4. Cauline leaves sessile, base auriculate or amplexicaul

       .. *B. napus* L. (유채)

5. Vein of fruit valves 1

.. *Brassica* L. (배추속)
4. Cauline leaves sessile or petiolate, base not auriculate or amplexicaul
5. Plant glabrous; stems branched distally; basal leaves not persistent, blade pinnatifid to pinnately lobed, lobes 1–3 each side; fruit completely dehiscent at maturity; seed coat not mucilaginous when wetted

\[ \ldots \]
\[ B. \text{juncea} \ (L.) \ Czern. \ (גַּנְבַּךְ) \]

5. Plant hirsute proximally; stems branched basally and distally; basal leaves persistent, blade deeply pinnatisect, lobes 4–8 each side; fruit partly indehiscent at mature; seeds coat mucilaginous when wetted

\[ \ldots \]
\[ B. \text{tournefortii} \ (סַּּאֲדָּלָּגְּגַּת) \]

**Acknowledgments**

This study was supported by the project “Research on landscape genetics and distribution of invasive alien plants in Korea according to climate change (KNA1-2-39, 21-2)” funded by the Korea National Arboretum. We sincerely thank Dr. Yong-Chan Cho and Dr. Yoon-Young Kim for their constructive criticism and valuable comments, which were of great help in revising the manuscript.

**Conflict of Interest**

The authors declare that there are no conflicts of interest.

**Literature Cited**

Abd El-Gawad, A. M. 2014. Ecology and allelopathic control of \textit{Brassica tournefortii} in reclaimed areas of the Nile Delta, Egypt. Turkish Journal of Botany 38: 347–357.

Abdelhanseed, A., W. Amer, W. Hassan and A. Aboellil. 2020. Auto-taxonomy of \textit{Brassica tournefortii} Gouan. (Brassicaceae) in Egypt. Bangladesh Journal of Plant Taxonomy 27: 233–250.

Al-Shehbaz, I. A. 2012. A generic and tribal synopsis of the \textit{Brassicaceae} (Cruciferae). Taxon 61: 931–954.

Al-Shehbaz, I. A., K. Arai and H. Ohba. 2006a. Cruciferae. In Flora of Japan, Vol. 2a. Iwatsuki, K., D. E. Bouffor and H. Ohba (eds.), Kodansha, Tokyo. Pp. 454–511.

Al-Shehbaz, I. A., M. A. Beilstein and E. A. Kellogg, 2006b. Systematics and phylogeny of the \textit{Brassicaceae} (Cruciferae): An overview. Plant Systematics and Evolution 259: 89–120.

Alcaraz Ariza, F. J., T. E. Díaz González, S. Rivas Martínez and P. Sánchez Gómez. 1989. Datos sobre la vegetación del sureste de España: Provincia biogeográfica Murciano-Almeriense. Itinerar Geobotanica 2: 5–133.

Alfaro, B. and D. L. Marshall. 2019. Phenotypic variation of life-history traits in native, invasive, and landrace populations of \textit{Brassica tournefortii}. Ecology and Evolution 9: 13127–13141.

Álvarez, I. and J. F. Wendel. 2003. Ribosomal ITS sequences and plant phylogenetic inference. Molecular Phylogenetics and Evolution 29: 417–434.

Bangle, D. N., L. R. Walker and E. A. Powell. 2008. Seed germination of the invasive plant \textit{Brassica tournefortii} (Sahara mustard) in the Mojave Desert. Western North American Naturalist 68: 334–342.

Barrows, C. W., E. B. Allen, M. L. Brooks and M. F. Allen. 2009. Effects of an invasive plant on a desert sand dune landscape. Biological Invasions 11: 673–686.

Beilstein, M. A., I. A. Al-Shehbaz and E. A. Kellogg. 2006. \textit{Brassicaceae} phylogeny and trichome evolution. American Journal of Botany 93: 607–619.

Berry, K. H., T. A. Gowan, D. M. Miller and M. L. Brooks. 2014. Models of invasion and establishment for African mustard (\textit{Brassica tournefortii}). Invasive Plant Science and Management 7: 599–616.

Chauhan, B. S., G. Gill and C. Preston. 2006. African mustard (\textit{Brassica tournefortii}) germination in southern Australia. Weed Science 54: 891–897.

Choudhary, B. R. and P. Joshi. 2001. Crossability of \textit{Brassica tournefortii} and \textit{B. rapa}, and morphology and cytology of their F1 hybrids. Theoretical and Applied Genetics 102: 1123–1128.

Curtis, C. A. and B. A. Bradley. 2015. Climate change may alter both establishment and high abundance of red brome (\textit{Bromus rubens}) and African mustard (\textit{Brassica tournefortii}) in the semiarid southwest United States. Invasive Plant Science and Management 8: 341–352.

Dahlin, K., E. König, A. Laubmeier, A. Wehn and K. Ríos-Soto. 2012. Competition Model between the Invasive Sahara Mustard and Native Plants in the Sonoran Desert. Society for Advancement of Chicanos/Hispanics and Native Americans in Science, Santa Cruz, CA, 38 pp.

Hijmans, R. J., S. Phillips, J. Leathwick and J. Elith. 2016. Dismo: Species distribution modelling. R package version 1.0-15. Retrieved Feb. 10, 2022, available from https://CRAN.R-project.org/package=dismo.

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate Change 2013 of the Physical Science Basis. Contribu-
tion of Working Group I to the Fifth Assessment Report of Intergovernmental Panel for Climate Change. Summary for Policy Makers. Cambridge University Press, Cambridge. Pp. 1–29.

Kadereit, J. W. 1994. Molecules and morphology, phylogenetics and genetics. Botanica Acta 107: 369–373.

Kraus, F., W. Daniel, L. J. Wong and S. Pagad. 2020. Global register of introduced and invasive species - United States of America (contiguous). Version 1.4. Invasive Species Specialist Group ISSG. Retrieved Aug. 19, 2022, available from https://www.isissg.org/

Leadlay, E. A. and V. H. Heywood. 1990. The biology and systematics of the genus Coincya Porta & Rigo ex Rouy (Cruciferae). Botanical Journal of the Linnean Society 102: 313–398.

Lei, Y. M., K. M. Dlugosch and B. J. Enquist. 2015. Novel spatial analysis methods reveal scale-dependent spread and infer limiting factors of invasion by Sahara mustard. Ecography 38: 311–320.

Liaw, A. and M. Wiener. 2002. Classification and regression by randomForest. R News 2: 18–22.

Lillian, S. 2017. Associational susceptibility of a native shrub, Atriplex canescens, mediated by an invasive annual forb, Brassica tournefortii, and invasive stinkbug, Bagrada hilaris. PhD dissertation, University of California, Riverside, CA, USA, 141 pp.

Lim, C.-H., S.-H. Jung, S.-Y. Jung, N.-S. Kim and Y.-C. Cho. 2020. Selection of optimal models for predicting the distribution of invasive alien plants species (IAPS) in forest genetic resource reserves. Korean Journal of Environment and Ecology 34: 589–600.

Malusa, J., B. Halvorson and D. Angell. 2003. Distribution of the Exotic Mustard Brassica tournefortii in the Mohawk Dunes and Mountain, Arizona. University of Arizona, Tucson, AZ, 7 pp.

Marushia, R. G. 2009. Brassica tournefortii: Phenology, interactions and management of an invasive mustard. PhD dissertation, University of California, Riverside, CA USA, 155 pp.

Marushia, R. G., M. L. Brooks and J. S. Holt. 2012. Phenology, growth, and fecundity as determinants of distribution in closely related nonnative taxa. Invasive Plant Science and Management 5: 217–229.

Meyer, D., E. Dimitriadou, K. Hornik, A. Weingessel and F. Leisch. 2015. e1071: Misc functions of the department of statistics, probability theory group (formerly: E1071), TU Wien. R package version 1.6-7. Retrieved Feb. 10, 2022, available from https://CRAN.R-project.org/package=e1071.

Milborrow, S. 2016. earth: Multivariate adaptive regression splines. R package version 4.4.4. Retrieved Feb. 10, 2022, available from https://CRAN.R-project.org/package=earth.

Moran, E. V. and J. M. Alexander. 2014. Evolutionary responses to global change: Lessons from invasive species. Ecology Letters 17: 637–649.

Nagpal, R., T. H. Dar and S. N. Raina. 2008. Molecular systematics of Brassica and allied genera in subtribes Brassicinae, Raphaninae, Moricandiinae, and Cakilinae (Brassicaceae, tribe Brassiceae): The organization and evolution of ribosomal gene families. Botanical Journal of the Linnean Society 157: 545–557.

Oh, B. U. 2007. Brassicaceae. In Genera of Vascular Plants of Korea. Flora of Korea Editorial Committee (ed.), Academy Publishing Co., Seoul. Pp. 427–461.

Park, J. S. and B. H. Choi. 2020. Estimating distribution changes of ten coastal plant species on the Korean Peninsula. Korean Journal of Plant Taxonomy 50: 154–165.

POWO. 2022. Plants of the World Online. Published on the Internet. Retrieved Aug. 19, 2022, available from http://www.plantsoftheworldonline.org.

Qi, X.-H., M.-F. Zhang and J.-H. Yang. 2007. Molecular phylogeny of Chinese vegetable mustard (Brassica juncea) based on the internal transcribed spacers (ITS) of nuclear ribosomal DNA. Genetic Resources and Crop Evolution 54: 1709–1716.

R Core Team. 2015. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved Feb. 10, 2022, available from https://www.R-project.org/.

Rahmani, R., M. Neji, A. O. Belgacem and M. Debouba. 2020. Potential distribution and the habitat suitability of the African mustard (Brassica tournefortii) in Tunisia in the context of climate change. Arabian Journal of Geosciences 13: 512.

Ridgeway, G. 2015. gbm: Generalized boosted regression models. R package version 2.1.1. Retrieved Feb. 10, 2022, available from https://CRAN-R-project.org/package=gbm.

RStudio Team 2021. RStudio: Integrated Development Environment for R. RSstudio, PBC, Boston, from http://www.rstudio.com/.

Salariato, D. L., F. O. Zuloaga and I. A. Al-Shehbaz. 2013. Revision and tribal placement of the Argentinean genus Paradio-doxa (Brassicaceae). Plant Systematics and Evolution 299: 305–316.

Sánchez-Flores, E. 2007. GARP modeling of natural and human factors affecting the potential distribution of the invasives Schismus arabicus and Brassica tournefortii in ‘El Pinacate y Gran Desierto de Altar’ Biosphere Reserve. Ecological Modelling 204: 457–474.

Schiermeier, Q. 2005. Pall hangs over desert's future as alien weeds fuel wildfires. Nature 435: 724.

Shrestha, U. B. and K. S. Bawa. 2014. Impact of climate change on potential distribution of Chinese caterpillar fungus (Ophio-
cordyceps sinensis) in Nepal Himalaya. PLoS ONE 9: e106405.

Steers, R. J. 2008. Invasive plants, fire succession, and restoration of creosote bush scrub in Southern California. PhD dissertation, University of California, Riverside, CA, USA, 209 pp.

The Plant List. 2013. Version 1.1. Published on the Internet. Retrieved Aug. 19, 2022, available from http://www.theplant-list.org.

Therneau, T., B. Atkinson and B. Ripley. 2015. rpart: Recursive partitioning and regression trees. R package version 4.1-10. Retrieved Feb. 10, 2022, available from https://CRAN.R-project.org/package=rpart.

Trader, M. R., M. L. Brooks and J. V. Draper. 2006. Seed production by the non-native Brassica tournefortii (Sahara mustard) along desert roadsides. Madroño 53: 313–320.

VanTassel, H. L. H., A. M. Hansen, C. W. Barrows, Q. Latif, M. W. Simon and K. E. Anderson. 2014. Declines in a ground-dwelling arthropod community during an invasion by Sahara mustard (Brassica tournefortii) in aeolian sand habitats. Biological Invasions 16: 1675–1687.

Venables, W. N. and B. D. Ripley. 2002. Modern Applied Statistics with S. 4th ed. Springer, New York, 495 pp.

Warwick, S. I., K. Mummenhoff, C. A. Sauder, M. A. Koch and I. A. Al-Shehbaz. 2010. Closing the gaps: Phylogenetic relationships in the Brassicaceae based on DNA sequence data of nuclear ribosomal ITS region. Plant Systematics and Evolution 285: 209–232.

Winkler, D. E., J. R. Gremer, K. J. Chapin, M. Kao and T. E. Huxman. 2018. Rapid alignment of functional trait variation with locality across the invaded range of Sahara mustard (Brassica tournefortii). American Journal of Botany 105: 1188–1197.

Winkler, D. E., K. J. Chapin, O. François, J. D. Garmon, B. S. Gaut and T. E. Huxman. 2019. Multiple introductions and population structure during the rapid expansion of the invasive Sahara mustard (Brassica tournefortii). Ecology and Evolution 9: 7928–7941.

Wood, S. N. 2006. Generalized Additive Models: An Introduction with R. Chapman & Hall/CRC, Boca Raton, 53 pp.