Four Unrecorded *Aspergillus* Species from the Rhizosphere Soil in South Korea

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**ABSTRACT**
The genus *Aspergillus* is commonly isolated from various marine and terrestrial environments; however, only a few species have been studied in rhizosphere soil. As part of the Korean indigenous fungal excavation project, we investigated fungal diversity from rhizosphere soil, focusing on *Aspergillus* species. A total of 13 strains were isolated from the rhizosphere soil of three different plants. Based on phylogenetic analysis of \(\beta\)-tubulin and calmodulin and morphological characteristics, we identified five *Aspergillus* species. *A. calidoustus* and *A. pseudodeflectus* were commonly isolated from the rhizosphere soil. Four species were confirmed as unrecorded species in Korea: *A. calidoustus*, *A. dimorphicus*, *A. germanicus*, and *A. pseudodeflectus*. The detailed morphological descriptions of these unrecorded species are provided.

**1. Introduction**
*Aspergillus* is one of the most common fungi in various environments worldwide. *Aspergillus* is known as plant and human pathogen, mycotoxin producer, and food spoiler. However, it plays important roles in the ecological and industrial systems by producing antibiotics and organic acids, and degrading starches, celluloses, and other polysaccharides [1–5]. Morphological characters such as growth rate, color of the colony, thermostolerance, and size of conidial heads and conidia are known to be important features for initial identification of *Aspergillus* [6]. However, morphological feature is not enough to recognize species because their morphological characteristics vary by their ecological habitats [6,7]. For accurate identification of *Aspergillus*, standardized methods including morphology, molecular analysis, and extrolite profiling have been proposed. DNA markers such as the internal transcribed spacer region, calmodulin (CaM), \(\beta\)-tubulin (BenA), and the RNA polymerase II second largest subunit (RPB2) have been used in *Aspergillus* identification and phylogeny [8]. According to the current research, the genus consists of six subgenera, 27 sections, and 446 species worldwide [9]. In Korea, 69 *Aspergillus* species have been reported [10–14]. Although some species have been reported from soil in terrestrial, marine, and clinical environments [15–18], many *Aspergillus* were isolated from food fermentation such as meju and nuruk [12,19–21]. Nonetheless, study on *Aspergillus* from rhizosphere soil in Korea is limited [22].

Fungi in rhizosphere environments play an important role in plant growth and adaptation [23,24]. *Aspergillus* is one of the common fungi in rhizosphere soil [25–31]. Some *Aspergillus* are known to produce plant promoting chemicals such as gibberellic acid and indole acetic acid [27,28]. Many *Aspergillus* strains were only identified at the genus level, as previous studies mainly focused on bioactive compounds [27–30]. Therefore, the diversity of *Aspergillus* in rhizosphere soil is unclear.

This project is organized by the National Institute of Biological Resources to excavate Korean indigenous fungi from the rhizosphere soil. We explored fungal diversity from rhizosphere soil of various plants; *Aspergillus*, *Penicillium*, *Trichoderma*, and *Fusarium* were common genera. Recently, we reported on diversity of *Penicillium*, revealing eight unrecorded species in Korea [32]. The main purpose of this study was to focus on *Aspergillus* in the rhizosphere of various plants and to identify them based on BenA and CaM loci. We discovered four unrecorded species: *A. calidoustus*, *A. dimorphicus*, *A. germanicus*, and *A. pseudodeflectus*.

**2. Materials and methods**

**2.1. Sample collections and isolation**
Rhizosphere soil of three plants (*Calystegia soldanella*, *Orobanche coerulescens*, and *Sorbus commixta*)...
were collected from five sites in Korea in 2019 (Table 1). Five grams of soil for each sample was diluted tenfold in sterile water. A 100 μL of each dilute was plated on dichloran rose bengal chloramphenicol agar (DRBC; Difco, Becton Dickinson). All plates were incubated at 25 °C for 7 days. Based on morphology, Aspergillus-like strains were transferred to potato dextrose agar (PDA; Difco, Becton Dickinson) plate. Strains were stored in 20% glycerol at −80 °C at the Seoul National University Fungus Collection (SFC).

2.2. DNA extraction, amplification, and sequencing

Genomic DNA was extracted from isolated Aspergillus using a modified cetyltrimethylammonium bromide extraction protocol [33]. For the primer sets, Bt2a/Bt2b for BenA and CF1/CF4 or cmd5/cmd6 for CaM, were used [34–36]. PCR was performed in a C1000 thermal cycler (Bio-Rad, Richmond, CA, USA) with previously described methods [37]. The PCR products were purified using the ExpinTM PCR Purification Kit (GeneAll Biotechnology, Seoul, Korea), according to the guideline. DNA sequencing was performed using the PCR primers at Macrogen (Seoul, Korea), using an ABI Prism 3730 genetic analyzer (Life Technologies, Gaithersburg, MD, USA).

2.3. Phylogenetic analysis

The sequences were assembled, proofread, and aligned using MEGA7 [38] and were deposited in GenBank (accession numbers in Table 2). Hamigeria avellanea CBS 295.48 was used as the outgroup [39]. Multiple alignments were performed using the default settings of the Multiple Alignment Fast Fourier Transform (MAFFT ver. 7) [40]. Then, each sequence was manually checked and adjusted. Maximum likelihood (ML) phylogenetic tree was performed with RAxML [41] implemented on CIPRES web portal [42], using the GTR + GAMMA model of evolution with 1000 bootstrap replicates.

2.4. Morphological analysis

Morphological analysis of the four unrecorded species was performed on three different culture media using previously described methods: Czapek yeast autolysate agar (CYA); yeast extract, Difco), malt extract agar (MEA; Oxoid), and yeast extract sucrose agar (YES; yeast extract, Difco). The Methuen Handbook of Color was used for the color names and alphanumeric codes for macromorphological characteristics [43]. The microscopic observation was processed under a light microscope (Eclipse 80i, Nikon, Tokyo, Japan) using the samples grown on MEA and CYA.

3. Results

3.1. Species identification

A total of 13 Aspergillus strains were isolated from rhizosphere of three plants. Based on the combined dataset of BenA and CaM sequences, they were identified as five species in two sections with four unrecorded species in Korea (Table 1 and Figures 1 and 2). Twelve strains were included in section Usti and were identified as four species: A. calidoustus (5 strains), A. germanicus (1), A. insuetus (1), and A. pseudodefectus (5). A. calidoustus, A. germanicus, and A. pseudodefectus were unrecorded species in Korea. For section Cremei, one strain was discovered and identified as A. dimorphicus, which was unrecorded species in Korea. A. calidoustus and A. pseudodefectus were commonly isolated from the rhizosphere soil (Table 1). Aspergillus diversity was higher in rhizosphere soil of Calyptea soldanella compared to others. Although A. pseudodefectus was commonly isolated from C. soldanella and Sorbus commixta, generally, the Aspergillus diversity was found unique for each plant.

| Species          | Section | Strain               | Location                                                                 | Substrate                        |
|------------------|---------|----------------------|--------------------------------------------------------------------------|----------------------------------|
| A. calidoustus*  | Usti    | SFC20191113-NB113    | Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do                         | Calystega soldanella             |
|                  |         | SFC20191113-NB116    |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB135    |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB146,   | Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do                         | Cremesi                          |
|                  |         | NIBRF0000509071     |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB197,   | Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do                         | Calystega soldanella             |
|                  |         | NIBRF0000509286     |                                                                          | Cremesi                          |
| A. dimorphicus   | Cremei  | SFC20191113-NB100,   | Guryongpo-eup, Nam-gu, Pohang-si, Gyeongsangbuk-do                         | Orobanchae coerulescens          |
|                  |         | NIBRF0000509072     |                                                                          | Cremesi                          |
| A. germanicus    | Usti    | SFC20191113-NB098,   | Guryongpo-eup, Nam-gu, Pohang-si, Gyeongsangbuk-do                         | Orobanchae coerulescens          |
|                  |         | NIBRF0000509073     |                                                                          | Cremesi                          |
| A. insuetus      | Usti    | SFC20191113-NB013    | Guryongpo-eup, Nam-gu, Pohang-si, Gyeongsangbuk-do                         | Calystega soldanella             |
| A. pseudodefectus| Usti    | SFC20191113-NB114,   | Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do                         | Calystega soldanella             |
|                  |         | NIBRF0000509074     |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB115    |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB136    |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB156    |                                                                          | Cremesi                          |
|                  |         | SFC20191113-NB199,   | Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do                         | Calystega soldanella             |
|                  |         | NIBRF0000509287     |                                                                          | Cremesi                          |

*The unrecorded Aspergillus species in Korea are represented in bold.
3.2. Taxonomy

Aspergillus calidoustus Varga, Houbraken, & Samson (2008)

Description: Colony diameter, at 25 °C for 7 days, in mm: CYA 50–51; CYA 15 °C 12–13; CYA 30 °C 60–66; CYA 37 °C 8–12; MEA 51–54; YES 50–51 (Figure 3).

Colonies on CYA, lightly sulcate, moderate to good sporulation, floccose, greenish gray (27D2) elsewhere with 1 mm white margin, exudate brownish orange (6D8) to dark brown (6F8) droplets, soluble pigment absent, reverse color olive brown (4D3) at center and light yellow (1A4) elsewhere. Colonies on MEA, lightly sulcate, moderate sporulation, velvety with floccose at center, central part

### Table 2. Strains used for phylogenetic analyses in this study.

| Section of Aspergillus | Species                     | Strain                      | GenBank accession no. |
|------------------------|-----------------------------|-----------------------------|-----------------------|
| Cremei                 | A. arxii                    | CBS 525.83³                 | MN969365 MN969223     |
|                        | A. brunneouniseriatus       | NRRL 4273¹                  | EF652123 EF652138     |
|                        | A. chrysogenum              | NRRL 5501¹                  | EF652117 EF652129     |
|                        | A. chrysospermus            | NRRL 5084¹                  | EF652109 EF652136     |
|                        | A. citreus                  | CBS 140566¹                 | FR757517 LF876969     |
|                        | A. creeseus                 | NRRL 5081¹                  | EF652120 EF652125     |
|                        | A. dimorphus                | NRRL 3650¹                  | EF652111 EF652135     |
|                        |                             | **SFC20191113-NB100**       | MW711172 MW711185     |
|                        |                             | CBS 1405129                 | MK451246 MK451317     |
|                        | A. europeae                 | NRRL 35052                  | EU021672 EU021685     |
|                        | A. flaschentraegeri         | CBS 13439¹                  | LN099006 LN099007     |
|                        | A. goarkiporensis           | NRRL 3649¹                  | EF652114 EF652126     |
|                        | A. infatius                 | CBS 892.70³                 | FJ510084 FJ510929     |
|                        | A. itaconicus               | NRRL 161¹                   | EF652118 EF652140     |
|                        | A. koreanus                 | EML-GSNP1-1¹                 | KX216530 KX216528     |
|                        | A. pulvarius                | NRRL 5078¹                  | EF652121 EF652139     |
|                        | A. stromatoides             | CBS 500.65¹                 | FJ510384 FJ510392     |
|                        | A. tordus                   | CBS 433.93³                 | FJ51001 FJ511084      |
|                        | A. wentii                   | NRRL 375¹                   | EF652106 EF652131     |
| Usti                   | A. asper                    | CBS 140842¹                 | KT698838 KT698839     |
|                        | A. boeticus                 | NRRL 6250¹                  | HE615092 HE615117     |
|                        | A. calidoustus              | CBS 121601¹                 | FJ624456 HE615659     |
|                        |                             | **SFC20191113-NB113**       | MW711167 MW711176     |
|                        |                             | CBS 1405113                 | MW711161 MW711173     |
|                        |                             | **SFC20191113-NB116**       | MW711160 MW711175     |
|                        |                             | **SFC20191113-NB1135**      | MW711162 MW711174     |
|                        |                             | **SFC20191113-NB146**       | MW711163 MW711177     |
|                        |                             | **SFC20191113-NB197**       | MW711163 MW711177     |
|                        | E449/M09                    | HGG31688 HGG31695           |
|                        | E460                        | HG664949 HG664950           |
|                        | A. carlsbadensis            | IBT 1449³                   | FJ51179 FJ51126       |
|                        | A. collinsii                | CBS 140843¹                 | KT698843 KT698844     |
|                        | A. contaminans              | CBS 142451¹                 | LT594435 LT594435     |
|                        | A. deflectus                | NRRL 2206¹                  | EF652261 EF652349     |
|                        | A. elongatus                | NRRL 5176¹                  | EF652236 EF652414     |
|                        | A. germanicus               | DTO 27-D9¹                  | FJ511772 FJ511416     |
|                        |                             | **SFC20191113-NB098**       | MW711717 MW711784     |
|                        | A. granulosus               | NRRL 1932¹                  | EF652254 EF652342     |
|                        | A. heterothallicus          | NRRL 5096¹                  | EF652232 EF652411     |
|                        | A. insuetus                 | NRRL 279¹                   | EF652281 EF652369     |
|                        | A. insuetus                 | NRRL 5096¹                  | EF652232 EF652411     |
|                        | A. kevei                    | CBS 209.92¹                 | EU076376 EU076385     |
|                        | A. keveloides               | CBS 132737¹                 | JN982694 JN982684     |
|                        | A. lucaksiewskensis         | NRRL 3491¹                  | EF652283 EF652371     |
|                        | A. monodii                  | CBS 435.93³                 | FJ511711 FJ511422     |
|                        | A. porphyrepistatus         | DTO 266-D9¹                 | KJ755380 KJ755380     |
|                        | A. pseudodefectus           | ET1611                      | KY853415 KY853415     |
|                        |                             | NRRL 6135¹                  | EF652321 EF652419     |
|                        |                             | **SFC20191113-NB114**       | MW711169 MW711178     |
|                        |                             | CBS 1405115                 | MW711166 MW711179     |
|                        |                             | **SFC20191113-NB136**       | MW711168 MW711182     |
|                        |                             | **SFC20191113-NB156**       | MW711164 MW711181     |
|                        |                             | **SFC20191113-NB199**       | MW711165 MW711180     |
|                        |                             | AS3 15308                   | JN982689 JN982679     |
|                        |                             | NRRL 278                    | EF652280 EF652368     |
|                        | A. pseudoustus              | IBT 2816¹                   | FJ51168 FJ51126       |
|                        | A. puniceus                 | NRRL 5077¹                  | EF652322 EF652410     |
|                        | A. siguranus                | CMV00494¹                   | MK451066 MK451512     |
|                        | A. thesauricus             | NRRL 62487¹                 | HE615095 HE615120     |
|                        | A. turkejensis              | CBS 504.65¹                 | FJ51191 FJ51145       |
|                        | A. ustus                    | NRRL 275¹                   | EF652279 EF652367     |

³ indicates the ex-type strains.

Sequences produced in this study are presented in bold letters.
gray (27B1) at center and greenish gray (27E2) elsewhere with 1 mm white margin, no exudates, soluble pigment absent, reverse color olive brown (4E4) and orange yellow (4B4) elsewhere. Colonies on YES, poor sporulation, velvety, central part color white to grayish yellow (5B4) at center, grayish yellow (4B4) to white at margin, no exudates, soluble pigment yellowish gray (3B2), reverse color yellowish white (2A2). Colonies on YES, lightly sulcate, good sporulation, floccose, olive yellow (3D6) elsewhere with 1 mm white margin, no exudates, soluble pigment absent, reverse color pastel yellow (3A4).

Conidiophores biseriate with smooth-walled, sinuous, light yellow, (3.7–) 4.4 (–6.1) μm wide; vesicles mostly globose to subglobose, (8.0–) 9.9 × 10.3 (–13.4) μm; conidial heads globose to loosely radiate, phialides (3.0–) 3.6 × 9.6 (–11.5) μm; conidia subglobose to globose with rough wall, 3.5 to 4.7 μm.

**Strain examined:** SFC20191113-NB100

**Remarks:** A. dimorphicus is morphologically similar to A. wentii, it can be distinguished from A. wentii by branched conidiophore with two vesicles [45].

**Aspergillus germanicus** Varga, Frisvad & Samson (2011)

**Description:** Colony diameter, at 25°C for 7 days, in mm: CYA 40–43; CYA 15°C 13–14; CYA 30°C 47–48; CYA 37°C 8–9; MEA 40–42; YES 45–48 (Figure 3).

Colonies on CYA, poor sporulation, floccose, orange gray (6B2) to white (26C1) at center, no exudates, soluble pigment yellowish gray (3B2), reverse color brownish gray (4E4) to pale yellow at margin (3A3). Colonies on MEA, poor sporulation, velvety, white, no exudates, soluble pigment absent, reverse color orange (5A7). Colonies on YES, poor sporulation, floccose to velvety, central part color white to grayish yellow (4B4) to white at center, no exudates, soluble pigment pale yellow (3A3), reverse color grayish orange (5B4) at center and grayish yellow (3C4) and light yellow (3A5).

Conidiophores biseriate with thick, smooth-walled, brown, (3.7–) 4.7 (–5.4) μm wide; vesicles septulate, (8.5–) 10.1 × 10.3 (–12.4) μm; conidial heads loosely columnar; metulae covering the upper half to three-fourths of upper surface, (2.3–) 3.2 × 5.2 (–5.8) μm; phialides (2.3–) 2.7 × 5.0 (–6.1) μm; conidia globose with brown smooth wall, (2.8–) 3.1 to 3.4 (–3.9) μm.

**Remarks:** A. calidoustus is morphologically similar to A. pseudodefectus and A. ustus. A. calidoustus was able to grow at 37°C, but A. ustus was not [44]. A. calidoustus can be distinguished from A. pseudodefectus by narrow margin and moderate or good sporulation in CYA.

**Aspergillus dimorphicus** B.S. Mehrotra & R. Prasad (1969)
Strain examined: SFC20191113-NB098

Remarks: A. germanicus is morphologically similar to A. thesauricus, it can be distinguished from A. thesauricus by growth at 37°C, thicker conidiophore, and smaller vesicle diameter [46].

Aspergillus pseudodeflectus Samson & Mouchacca (1975)

Description: Colony diameter, at 25°C for 7 days, in mm: CYA 49–51; CYA 15°C 10–13; CYA 30°C 57–59; CYA 37°C 14–18; MEA 47–48; YES 52–54 (Figure 3).

Colonies on CYA, lightly sulcate, poor to moderate sporulation, floccose, grayish orange (5B3) at center and white elsewhere, exudates dark brown (8F4), soluble pigment pale yellow (3A3), reverse color olive (3D3) at center and light yellow (2A5) elsewhere. Colonies on MEA, moderately sulcate, poor to moderate sporulation, floccose, brownish gray (5C2) and white at margin, no exudates, soluble pigment absent, reverse color brown (6E5) and golden yellow at margin (5B7). Colonies on YES, radially sulcate and wrinkled at center, poor to moderate sporulation, floccose, yellowish gray (4B2)

Figure 2. Maximum likelihood (ML) phylogenetic tree of Aspergillus sect. Usti based on the combined data set of BenA and CaM sequences. Bootstrap values >70 are presented at the nodes. The scale bar represents the number of nucleotide substitutions per site. "T" indicates the ex-type strains. Aspergillus reported in this study are represented in bold. The unrecorded Aspergillus species are accented in color box.
and white at margin, no exudates, soluble pigment pale yellow (3A3), reverse color deep yellow (4A8).

Conidiophores biseriate with short, curved, rough-walled, brown, (3.4–) 3.9 (–4.2) μm wide; vesicles globose to clavate, (6.7–) 7.9 × 9.5 (–10.5) μm; conidial heads brown, radiate; metulae more or less cylindrical, (2.4–) 3.6 × 4.6 (–5.4) μm; phialides (2.8–) 3.4 × 6.4 (–8.1) μm; conidia globose to ellipsoidal with thick-walled, brown, rough wall, (3.3–) 3.7 to 4.5 (–5.3) μm.

Strains examined: SFC20191113-NB114, SFC20191113-NB156, and SFC20191113-NB199.

Remarks: A. pseudodeflectus is morphologically similar to A. calidoustus. A. pseudodeflectus can be distinguished from A. calidoustus by wide margin and poor sporulation in CYA.

4. Discussion

The rhizosphere soil is a complex and dynamic environment that provides a close relationship between plants and microbes. A total of 13 Aspergillus strains were isolated from rhizosphere soil of three plants and were identified as five.

Figure 3. The unrecorded Aspergillus species in Korea: A. calidoustus (SFC20191113-NB146), A. dimorphicus (SFC20191113-NB100), A. germanicus (SFC20191113-NB098) and A. pseudodeflectus (SFC20191113-NB114). (a–c) Colonies grown on Czapek yeast autolysate agar (CYA), malt extract agar (MEA), and yeast extract sucrose agar (YES) from left to right (top = obverse, bottom = reverse). (d–f): Conidiophores; (g) Conidia (scale bar = 10 μm).
species in two sections including four unrecorded species based on BnaA and CalM sequences. Although 12 species in Aspergillus section Fumigati have been reported from arable soil [17], many previous studies only focused on limited environments, such as meju and nuruk [12,19–21]. Only Aspergillus terreus has previously been reported from rhizosphere soil of paprika plants in Korea [47]. Five additional species (A. calidoustus, A. dimorphicus, A. germanicus, A. insuetus, and A. pseudodeflectus) are reported for the first time in this study, from the rhizosphere soil in Korea.

Four species were unreported in Korea: A. calidoustus, A. dimorphicus, A. germanicus, and A. pseudodeflectus. A. calidoustus is commonly found in clinical environments, indoor air, and forest soil [44,48,49]. It has been isolated from Acanthospermum austral and is known for its antifungal and cytotoxic activity [50]. In this study, A. calidoustus was isolated from the rhizosphere soil of Calystegia soldanella and Sorbus commixta. A. pseudodeflectus was previously isolated from desert soil and seaweed [51,52]. It produced pseudodeflectusin, which exhibited cytotoxic activity [51]. In this study, A. pseudodeflectus strains were isolated from rhizosphere soil of Calystegia soldanella and Sorbus commixta. The A. pseudodeflectus strains isolated from Korea exhibited faster growth on YES compared to the other reported strains [53,54]. Some fungi isolated from different environments exhibit different metabolism and growth rates due to environmental adaptation [55,56]. A. germanicus was first isolated from indoor air, but there are few reports of the species so far [57]. In this study, A. germanicus was isolated from the rhizosphere soil of Orobanche coerulescens. Our study is the first report of the species from rhizosphere soil. A. dimorphicus was isolated from garden soil, loess soil, and deep-sea sediment [58–61]. A. dimorphicus showed antitumor activities [62] and proteolytic activities [63]. A. dimorphicus strain was isolated from the rhizosphere soil of Orobanche coerulescens in this study.

Aspergillus species are well known for their potential for usage in industrial and medical compounds, but many strains remain at the genus level. Therefore, we believe that our study will provide the basis for the discovery of new compound based on accurate identification of Aspergillus. Although many Aspergillus species have been found in rhizosphere soils using the NGS method [64–66], the role of Aspergillus in rhizosphere soil is unclear. To understand the interaction between Aspergillus and plants, further studies are needed to investigate the function of Aspergillus in rhizosphere soil.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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