Postprint of a Numerical Taxonomic Study of Glyptopetalum and Euonymus (Celastraceae)

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Abstract

The systematic relationships between the genus Euonymus L. and the genus Glyptopetalum Thw. have long been controversial. To clarify their relationships, this study selected 12 species of Glyptopetalum, 17 species of Euonymus, and 2 species of Microtropis Wall. ex Meisn., totaling 31 OTUs, measured and statistically analyzed 56 morphological characters, and conducted a numerical taxonomic study using cluster analysis (UPGMA) and principal coordinate analysis (PCoA) methods. The results indicate that Glyptopetalum and Euonymus exhibit high phenetic similarity, with transitional taxa between them including E. chloranthoides Yang and E. pallidifolium Hayata, as well as G. fengii (Chun & F. C. How) Ding Hou and G. geloniifolium (Chun & F. C. How) C. Y. Cheng. This study proposes that treating Glyptopetalum as a section of Euonymus—sect. Glyptopetalum—placed near sect. Ilicifolia is more reasonable. Principal coordinate ordination analysis of characters reveals that leaf length, leaf width, number of lateral leaf veins, number of petals, number of locules, number of ovules per locule, number of inflorescence branches, presence/absence of aril, capsule dehiscence, flowering period, and length of infructescence peduncle are important characters for the classification of Euonymus.

Full Text

Preamble

A Numerical Taxonomic Study of the Genera *Glyptopetalum* and *Euonymus* (Celastraceae)

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Abstract

The systematic relationship between the genera *Euonymus* L. and *Glyptopetalum* Thw. has long been controversial. To clarify their relationship, this study selected 12 species from *Glyptopetalum*, 17 species from *Euonymus*, and 2 species from *Microtropis* Wall. ex Meisn., totaling 31 operational taxonomic units (OTUs). We measured and analyzed 56 morphological characters using cluster analysis (UPGMA) and principal coordinate analysis (PCoA). The results demonstrate high phenetic similarity between *Glyptopetalum* and *Euonymus*, with transitional taxa including *Euonymus chloranthoides* Yang, *E. pallidifolius* Hayata, *Glyptopetalum fengii* (Chun & F. C. How) Ding Hou, and *G. geloniifolium* (Chun & F. C. How) C. Y. Cheng. This study proposes that *Glyptopetalum* should be treated as a section within *Euonymus*—*Euonymus* sect. *Glyptopetalum*—and placed near *E.* sect. *Ilicifolia*. Principal coordinate analysis of characters revealed that leaf blade length and width, number of lateral veins, petal number, locule number, ovules per locule, inflorescence branch number, presence/absence of aril, capsule dehiscence, flowering phase, and infructescence stalk length are taxonomically valuable for *Euonymus* classification.

Keywords: *Euonymus* L., *Glyptopetalum* Thw., morphological characters, numerical taxonomy, cluster analysis, principal coordinate analysis

Introduction

Euonymus belongs to the tribe Euonymeae of Celastraceae. Traditionally, the genus has been divided into five sections based primarily on capsule morphology: sect. *Uniloculares*, sect. *Melanocarya*, sect. *Echinococcus*, sect. *Ilicifolii*, and sect. *Euonymus*, comprising approximately 129 species. The type species is *Euonymus europaeus* L., distributed across subtropical and warm temperate regions of both hemispheres, with southwestern China representing its modern center of diversification and diversity (Cheng et al., 1999; Ma, 2001). *Glyptopetalum* was separated from *Euonymus* based on characteristics such as 4-merous flowers and one anatropous ovule per locule (Thwaites, 1856). Its type species is *Glyptopetalum zeylanicum* Thw., with about 40 species distributed across tropical and subtropical Asia. China hosts 10–13 species found in Guangxi, Yunnan, Hainan, and Taiwan—the northern margin of *Glyptopetalum* distribution (Hou, 1963; Cheng et al., 1999; Meng et al., 2012).

The systematic status of *Glyptopetalum* remains controversial. Some scholars maintain it as an independent genus based on multiple reproductive structural features: 4-merous flowers, one ovule per carpel, and seed raphe with 3–7 branches (Prain, 1891; Hou, 1962; Cheng et al., 1999; Meng et al., 2012; Simmons et al., 2012; Savinov, 2014). Others argue that *Euonymus* exhibits sufficient variation to encompass *Glyptopetalum*' s characteristics (Kurz, 1877; Baillon, 1880). Molecular phylogenetic studies using morphological characters and chloroplast genes (*matK*, *trnL-F*) and nuclear genes (ITS and 26S rDNA) showed that *Glyptopetalum* and *Euonymus* form a monophyletic group (Simmons et al., 2012). Li et al. (2014) analyzed 48 species of *Euonymus* and *Glyptopetalum* using two nuclear gene sequences (ITS and ETS) and three chloroplast gene regions (*psbA-trnH*, *rp136-infA-rps8*, and *trnC-ycf6*) with maximum parsimony and Bayesian inference, also supporting a monophyletic group. However, previous studies relied on only 2–3 *Glyptopetalum* species as representatives or limited molecular fragments, lacking systematic analysis including most *Glyptopetalum* species. As noted by Simmons et al. (2012), the relationship between *Glyptopetalum* and *Euonymus* requires further in-depth analysis.

Numerical taxonomy, established by Sokal and Sneath in the 1960s, has emerged as a major school alongside cladistics and evolutionary taxonomy. While not generating new systems itself, numerical taxonomy validates existing classifications, corrects erroneous views, and identifies previously overlooked useful characters (Zhong and Chen, 1991). This approach has resolved numerous taxonomic problems (Zhong and Chen, 1991; Dai et al., 1995; Xiong et al., 1997; Peng et al., 2007; Zhang et al., 2010; Chen et al., 2012) and has been applied to *Euonymus*, effectively reflecting interspecific relationships. For example, Zheng et al. (2012) conducted a numerical taxonomic analysis of *Euonymus* sect. *Echinococcus*, concluding that *E. hemsleyanus* should not be merged with *E. angustatus* and *E. echinatus*, nor *E. echinatus* with *E. subsessilis*. Yao (2018b) performed a numerical taxonomic analysis based on floral morphology, demonstrating the taxonomic value of ovule number per carpel. This study employs cluster analysis (UPGMA) and principal coordinate analysis (PCoA) to analyze relationships between *Euonymus* and *Glyptopetalum* in Celastraceae, exploring their systematic classification.

1.1 Materials

Most materials were obtained from the Herbarium of the Institute of Botany, Chinese Academy of Sciences (PE) and the Herbarium of the College of Life Sciences, Beijing Normal University (BNU), with some fresh materials collected by the authors. Field observations were conducted in Guangxi, Yunnan, and Hainan, yielding numerous character data. This study selected 12 *Glyptopetalum* species, 17 *Euonymus* species (including 3 from sect. *Ilicifolia*, 3 from sect. *Echinococcus*, 6 from sect. *Euonymus*, 3 from sect. *Melanocarya*, and 2 from sect. *Uniloculares*), and 2 *Microtropis* species, totaling 31 OTUs (Table 1). Since both *Euonymus* and *Microtropis* have opposite leaves and capsules but are phylogenetically distant (Simmons & Jennifer, 1999), *Microtropis* was selected as the outgroup for *Euonymus* and *Glyptopetalum*.

1.2 Methods

Quantitative characters were measured using rulers and digital calipers, while qualitative multistate characters were coded according to their states (Table 1). Following Zhong et al. (1990) principles for character selection in numerical taxonomy, we selected 36 binary characters, 9 continuous numerical characters, and

11 ordered multistate characters, totaling 56 characters (Table 2). Character selection and coding followed Zheng et al. (2012) and Li et al. (2013).

Cluster analysis and multivariate analysis were performed using NTSYS-pc 2.10e software (Rohlf, 2005). For cluster analysis: (1) raw data were transformed and standardized; (2) distance matrices were calculated; (3) cluster analysis was performed based on distance matrices to generate dendrogram matrices; (4) dendrogram matrices were compared with distance matrices using Mantel tests to calculate cophenetic distance matrices and correlation coefficients, indicating how well the dendrogram represented the original distance matrix; and (5) dendrograms were plotted using the UPGMA (unweighted pair-group method using arithmetic averages) algorithm.

For multivariate analysis: Principal component analysis (PCA) and principal coordinate analysis (PCoA) are commonly used in numerical taxonomy. Since PCA is unsuitable for discrete qualitative characters (Sneath & Sokal, 1973; Schilling & Heiser, 1976; Kent & Coker, 1992), PCoA has been increasingly applied in recent years (Sneath, 2000; Khalik et al., 2002; Sebola & Balkwill, 2009). Therefore, this study employed PCoA. The procedure involved: calculating correlation coefficients from the standardized matrix, then determining eigenvalues and eigenvectors of the correlation matrix, and finally obtaining factor loadings of characters on the first three principal coordinates. Three-dimensional scatter plots of the first three principal coordinates were generated using Origin 2018 software.

2.1 Cluster Analysis

UPGMA cluster analysis of 31 OTUs from *Euonymus*, *Glyptopetalum*, and *Microtropis* (Figure 1 [Figure 1: see original paper]) revealed eight major groups:

Group A includes two *Microtropis* species: *M. caudata* and *M. osmanthoides*. This group diverges from others at a linkage distance of 1.3, characterized by opposite, entire leaves, 5-merous flowers, white petals, thick short styles, 2 carpels, 2 ovules per locule, bilocular capsules, smooth pericarp, and absence of aril.

Group B includes *Euonymus schensianus* and *E. giraldii* from sect. *Uniloculares*, characterized by opposite leaves with ciliate serrations, multi-flowered cymes, 4-merous yellow-green flowers, 4 carpels, capsules with dorsal ridges extending into wings, non-curling pericarp after dehiscence, and seeds fully enclosed by orange-yellow aril.

Group C includes *E. alatus*, *E. centidens*, and *E. dielsianus* from sect. *Melanocarya*, characterized by opposite leaves, 4-merous pale yellow-green flowers, 1–2 ovules per locule, and aril enclosing more than half of the seed.

Group D includes *E. maackii* and *E. nitidus* from subsect. *Euonymus* and *E. myrianthus* and *E. grandiflorus* from subsect. *Multiovulatae* of sect. *Euonymus*, characterized by opposite, serrate leaves, 4-merous yellow-white flowers, 4–6 upright ovules per locule, shallowly lobed capsules, non-curling pericarp after dehiscence, and aril partially or fully enclosing seeds.

Group E includes *E. aculeatus*, *E. subsessilis*, and *E. scandens* from sect. *Echinococcus*, characterized by liana-like shrubs, opposite serrate leaves, 4-merous yellow-white flowers, more than 1 ovule per locule, spiny capsules, and aril fully enclosing seeds.

Group F includes *E. japonicus*, *E. bockii*, *E. theacolus*, and *E. pallidifolius* from sect. *Ilicifolia* and *G. fengii* and *G. geloniifolium* from *Glyptopetalum* sect. *Glyptopetalum*, characterized by opposite leaves with sparse serrations, 4-merous yellow-green flowers, short filaments, 1–2 anatropous ovules per locule, and round, smooth capsules.

Group G contains only *E. chloranthoides*, characterized by opposite serrate leaves, cymes with only 3 flowers, 5-merous purple flowers with irregular shallow teeth on petal margins, short filaments, 1–2 anatropous ovules per locule, shallowly lobed capsules, branched raphe, and aril enclosing most of the seed coat.

Group H primarily comprises species from *Glyptopetalum* sect. *Patelliformia*, characterized by opposite leaves, 4-merous flowers, 1 anatropous ovule per locule, persistent central axis after capsule dehiscence, outward-curling pericarp, aril enclosing nearly half of the seed, and branched raphe. This group divides into two subgroups: one including *G. rhytidophyllum*, *G. longipedicellatum*, *G. sclerocarpum*, *G. continentale*, *G. feddei*, and *G. reticulinerve*—arborescent species with leaves exceeding 15 cm; and another including *G. aquifolium*, *G. ilicifolium*, *G. lancilimbum*, and *G. longepedunculatum*—shrubby species with leaves less than 15 cm.

2.2 Principal Coordinate Analysis (PCoA)

PCoA results showed that the first two principal coordinates contributed 18.2652% and 14.3652% of the variance, respectively, with a cumulative contribution of 43.3994% for the first three axes. This indicates PCoA is suitable for analyzing *Euonymus*, *Glyptopetalum*, and *Microtropis*. As shown in Table 4 , characters with absolute loading values exceeding 0.6 on the first axis include leaf blade length and width, number of lateral veins, petal number, locule number, ovules per locule, presence/absence of aril, capsule dehiscence, flowering phase, and infructescence stalk length. On the second axis, leaf blade length, flowering phase, and ovules per locule had absolute loading values exceeding 0.65. On the third axis, inflorescence branch number and infructescence stalk length both exceeded 0.8.

The PCoA three-dimensional scatterplot (Figure 2 [Figure 2: see original paper]) revealed two major groups: *Microtropis* and a mixed group of *Glyptopetalum* and *Euonymus*. Along the first axis (accounting for 18.2652% of total variance), *Glyptopetalum* gradually transitions to *Euonymus* without clear boundaries, with transitional species including *G. geloniifolium*, *G. fengii*, *E. chloranthoides*, and members of *E.* sect. *Ilicifolia* such as *E. pallidifolius*, *E. japonicus*, and *E. theacolus*. Along the second axis (14.3652% of total variance), *Euonymus* and *Glyptopetalum* are completely intermixed.

Discussion

Cluster analysis (UPGMA) of 56 characters divided *Glyptopetalum* into two groups, consistent with *Flora Reipublicae Popularis Sinicae* (Cheng et al., 1999): sect. *Patelliformia* and sect. *Glyptopetalum*. *Euonymus* was divided into six groups, with sect. *Echinococcus*, sect. *Kalonymus* (syn. *Uniloculares*), sect. *Melanocarya*, and sect. *Euonymus* each forming distinct clusters. Thus, cluster analysis results generally align with previous studies (Cheng et al., 1999; Ma, 2001). However, contrary to many scholars' expectations, *Glyptopetalum* and *Euonymus* did not separate into two distinct major groups but rather intermingled. Notably, *Glyptopetalum* sect. *Glyptopetalum* species *G. fengii* and *G. geloniifolium* clustered with several representatives of *E.* sect. *Ilicifolia* due to similar fruit ornamentation, both belonging to the round-fruit type. *Euonymus chloranthoides* was positioned within *Glyptopetalum*, intermediate between its two sections. The dendrogram thus reveals the strongest phenetic similarity between *Glyptopetalum* and *E.* sect. *Ilicifolia*.

Principal coordinate ordination showed that although *Glyptopetalum* and *Euonymus* species each formed loose aggregations, they were arranged very closely throughout the ordination space without clear boundaries. In the ordination plot, *G. fengii* and *G. geloniifolium* were intermixed with *E. pallidifolius*, *E. bockii*, *E. japonicus*, *E. theacolus*, and *E. chloranthoides* from *E.* sect. *Ilicifolia*. *Glyptopetalum fengii* and *G. geloniifolium* possess distinctly branched seed raphe and 4-merous flowers. *Euonymus chloranthoides* has bubble-wrinkled petals, aril enclosing most of the seed and concolorous with the seed coat, and branched raphe—characteristics of *Glyptopetalum*—but also exhibits 5-merous flowers and 1–2 ovules per locule, resembling *Euonymus* (Cheng et al., 1999). Both cluster analysis and PCoA show uncertain placement of *E. chloranthoides*: in the phenogram it lies outside other *Euonymus* and *Glyptopetalum* species, intermediate between *Microtropis* and the *Euonymus*-*Glyptopetalum* complex, while in the ordination plot it falls between the two genera. Based on combined evidence, we consider *E. chloranthoides* a transitional species between *Euonymus* and *Glyptopetalum*.

Euonymus pallidifolius was traditionally placed in *Euonymus* (Lu & Yang, 1993; Cheng et al., 1999; Ma, 2001; Liu & Funston, 2008), but its branched raphe, one ovule per locule, and 4-merous flowers led Meng et al. (2012) to transfer it to *Glyptopetalum*. Our results also show *E. pallidifolius* is phenetically closer to *Glyptopetalum*. *Euonymus bockii* has 4-merous flowers and maculate capsules but fully arillate seeds and unbranched raphe. Extensive fieldwork and herbarium studies during our taxonomic revision of Chinese *Glyptopetalum* revealed additional transitional species: 4-merous flowers in *E. maackii* Rupr.; one anatropous ovule per locule in *E. venosus* Hemsl.; maculate capsules in *E. bockii* Loes.; and branched raphe in *E. chloranthoides* Yang. These findings align with cluster and ordination analyses, confirming extensive character overlap between *Glyptopetalum* and *E.* sect. *Ilicifolia* with transitional species exhibiting intermediate features.

Yao et al. (2018a, 2018b) found similar floral disc structures in *Euonymus* and *Glyptopetalum*, with maculate capsules in most *Glyptopetalum* species and some *E.* sect. *Ilicifolia* species being developmentally homologous to spines in sect. *Echinococcus*—both derived from floral disc development. Pollen studies also revealed high morphological similarity between *Glyptopetalum* and *Euonymus*, particularly sect. *Ilicifolia* (Zhang et al., 2018). Integrating our UPGMA and PCoA results based on 56 characters (including leaf epidermal micromorphology and macro-morphology) with molecular phylogenetic studies (Simmons et al., 2012; Li et al., 2014) and Meng' s (2010) comparative study of seed coat micromorphology, we propose merging *Glyptopetalum* into *Euonymus* and placing it near sect. *Ilicifolia*.

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Note: Figure translations are in progress. See original paper for figures.