

A COMPARATIVE STUDY OF ACHENE MORPHOLOGY IN KOREAN POLYGONACEAE

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Abstract

A comparative macro- and micromorphological study was conducted on achenes of Korean Polygonaceae comprising 45 taxa under 10 genera using a Stereo-microscope (SM) and Scanning Electron Microscope (SEM) to evaluate the taxonomical relevance of achene morphological characteristics. The achene shape is lenticular, biconvex, trigonous, or spheroidal. The largest achenes are found in *Fagopyrum esculentum* Moench (5.80–6.70 × 3.90–4.40 mm) and *Rheum rhabarbarum* L. (5.00–6.50 × 4.00–5.20 mm), and the smallest is found in *Rumex maritimus* L. (1.17–1.41 × 0.60–0.84 mm). Three types of embryo shape (curved, straight, and folded) and two types of embryo position (plane and parietal) can be distinguished. Most taxa have a curved embryo shape with plane position. Four types of surface patterns (smooth, papillae, tuberculate, or small pits) are observed. The surface sculpture or embryo type is rather consistent at the generic or tribal level, and the comprehensive consideration of achene characteristics is also useful at the species level. The achene morphology is described in detail, compared, and illustrated. The taxonomic significance of the achene morphology is discussed.

Introduction

Polygonaceae Juss. consists of ca. 1,200 species in 48 genera and has a worldwide distribution (Freeman and Reveal, 2005). The family Polygonaceae is usually divided into subfamilies Eriogonoideae Arnott and Polygonoideae Eaton (Freeman and Reveal, 2005), and the subfamily Symmerioideae Meisn. was suggested based on recent molecular phylogeny with number of stamens and pyramidal achene (Brandbyge, 1993; Sanchez *et al.*, 2011). The Polygonoideae has been characterized by herb or sub-shrubs, the presence of ochreae and swollen nodes, flowers subtended by bracteoles but not enclosed in involucre, and cosmopolitan distribution (Haraldson, 1978; Freeman and Reveal, 2005; Sanchez *et al.*, 2011). The subfamily is also consistently confirmed by molecular sequence data (Sanchez *et al.*, 2009, 2011).

However, the taxonomic circumstance of intra-subfamily in Polygonoideae (e.g., tribal, generic, or sectional level) have been controversial, and new tribal compositions were suggested according to recent molecular phylogenetic studies (Freeman and Reveal, 2005; Sanchez *et al.*, 2009, 2011; Schuster *et al.*, 2015). For example, the proposed taxonomic system by these studies consist of five to seven tribes, such as Calligoneae C.A. Mey, Fagopyreae Yoneak., Oxygoneae T.M. Schust. & Reveal, Persicariae Dumort., Polygoneae Rchb., Pteroxygoneae T.M. Schust. & Reveal and Rumiceae Dumort. (*matK*, *ndhF* and *rbcL*, Sanchez *et al.*, 2011; ITS, *matK* and *trnL-F*,

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Schuster *et al.*, 2015). The taxonomic composition in the Persicarieae or Polygoneae is also most controversial as large group within Polygonoideae, namely the generic or sectional delimitation of these tribes are constantly changing (Hedberg, 1946; Haraldson, 1978; Brandbyge, 1993; Lamb Frye and Kron, 2003; Li *et al.*, 2003; Park and Hong, 2007; Sanchez *et al.*, 2011). For example, *Persicaria* was treated into *Polygonum s.l.* (Li *et al.*, 2003; Zhu *et al.*, 2007), however recent studies suggested that *Persicaria* is separated as independent genus (Haraldson, 1978; Ronse Decraene *et al.*, 2000; Lamb Frye and Kron, 2003). *Aconogonon* and *Bistorta* were merged into *Polygonum* in some studies (Li *et al.*, 2003; Park and Hong, 2007), while *Aconogonon* and *Bistorta* were usually recognized as independent genera (Hedberg, 1946; Haraldson, 1978; Freedman and Reveal, 2005). However, a recent molecular study treated *Aconogonon* as a section of *Koenigia* (Schuster *et al.*, 2015). Various research approaches have been attempted to clarify the taxonomic positions within the Polygonoideae; thus, a comparative study of the morphological characteristics or re-evaluation of recently suggested taxonomic system is necessary to determine taxonomic delimitation.

The importance of fruit and seed morphology in flowering plants has been recognized for systematic information at various taxonomic levels; furthermore, several recent studies have shown the phylogenetic value of fruit and seed characteristics (Donoghue *et al.*, 2004; Jacobs *et al.*, 2008, 2010; Choi *et al.*, 2012; Song *et al.*, 2015). The description of anatomical features or micromorphology of the achenes of Polygonaceae were often performed, but only these were performed on represented taxa or regional taxa (e.g., Ronse Decraene *et al.*, 2000; Yurteseva, 2001; Hou *et al.*, 2007; Kantachot and Chantaranothai, 2011), or were simply described without any taxonomic implications (Martin, 1946, 1954). The Korean Polygonaceae is known to that consist of 85 taxa (10 genera) which belong to the tribes Fagopyreae, Persicarieae, Polygoneae and Rumiceae (except Calligoneae, Oxygoneae and Pteroxygoneae) within the subfamily Polygonoideae (Chang *et al.*, 2014; Schuster *et al.*, 2015). However, the study of achene morphology in Korean Polygonaceae has been mainly in the form of brief notes or only on sectional or generic level (Kim *et al.*, 2001; Nakayama *et al.*, 2004; Lee *et al.*, 2010), and is still lacking comprehensive discussion. Thus, the present study aims to investigate and provide detailed descriptions of achene macro- and micromorphology in the selected Korean Polygonaceae, and to evaluate the taxonomic or diagnostic importance of fruit morphological features.

Materials and Methods

The achene morphology of 45 taxa from 10 genera in the Korean Polygonaceae (Table 1) was investigated. The achenes were collected from herbarium specimens of KH and KHUS, and donated from the seed bank of the Korean National Arboretum, Pocheon, South Korea [see Table 1; abbreviations according to Thiers (2018) and continuously updated].

Fully matured fruits were selected and observed under a stereomicroscope (SM; SteREO Discovery.V8; Carl Zeiss Microscopy GmbH, Germany) to confirm their normality and taxon identification. Cross-sections of the achenes were also taken, and examined under a SM. To observe detailed sculpturing patterns of the achenes, dry fruits were rehydrated overnight in the Agepon wetting agent (Agepon[®]:DW = 1:200), and fresh fruits were fixed in FAA (formaldehyde: acetic acid: alcohol) for 48 h, and stored in 70 % ethanol. Prepared achenes were dehydrated through an ethanol series (in 50 %, 70 %, 90 %, and 95 % ethanol for 10 min each and in absolute ethanol for about 20 min) and then replaced ethanol with carbon dioxide for critical point drying

Table 1. Voucher specimens of the Korean Polygonaceae that are examined in the present study (Some taxa have only seed bank management number).

Taxon	Voucher specimens
Aconogonon (Meisn.) Rchb.	
<i>A. alpinum</i> (All.) Schur	Korea, Chungcheongnam-do, Oct.2002, G.W. Seo and J.Y.Kim (KH-154)
<i>A. divaricatum</i> (L.) Nakai ex T. Mori	Korea, Gyunggi-do, Oct.2004, J.Y. Kim (KH-L1455)
Bistorta (L.) Scop.	
<i>B. manshuriensis</i> (Petrov ex Kom.) Kom.	Korea, Gyunggi-do, Aug.2006, J.Y. Kim (KH-L2769)
Fagopyrum Mill.	
<i>F. esculentum</i> Moench	Korea, Is. Jeju, Oct. 2011, S.H. Kang 111024004 (KH)
Persicaria (L.) Mill.	
<i>P. chinensis</i> (L.) H. Gross var. <i>chinensis</i>	Korea, Is, Jeju, Nov. 2012, M.J. Kongs, n. (KHUS)
<i>P. dissitiflora</i> (Hemsl.) H. Gross ex T. Mori	Korea, Gyunggangbuk-do, Sep.2012, S.G. Son and H.W.Choi (KH-L10091)
<i>P. filiformis</i> (Thunb.) Nakai	Korea, Gyunggi-do, Sep.2005, J.Y. Kim (KH-L2208)
<i>P. hydropiper</i> (L.) Delarbre	Korea, Gyunggi-do, Oct.2002, G.W. Seo and J.Y. Kim (KH-L153)
<i>P. japonica</i> (Meisn.) Nakai	Korea, Gyunggi-do, Nov.2004, J.Y. Kim (KH-L1835)
<i>P. lapathifolia</i> (L.) Delarbre var. <i>lapathifolia</i>	Korea, Gyunggi-do, Sep.2012, J.Y. Kim (KH-L10035)
<i>P. lapathifolia</i> var. <i>salicifolia</i> (Sibthorp) Miyabe	Korea, Incheon, Nov.2014, S.H. Park <i>et al.</i> (KH-L14267)
<i>P. longiseta</i> (Bruijn) Kitag.	Korea, Gyunggangbuk-do, Sep.2004, G.W. Seo <i>et al.</i> (KH-L1329)
<i>P. maackiana</i> (Regel) Nakai ex T. Mori	Korea, Gyunggangnam-do, Oct.2012, S.D. Lee (KH-L10050)
<i>P. muricata</i> (Meisn.) Nemoto	Korea, Gyunggi-do, Oct.2007, J.Y. Kim (KH-L3238)
<i>P. nepalensis</i> (Meisn.) H. Gross	Korea, Gangwon-do, Sep.2011, M.S. Kim <i>et al.</i> (KH-L8969)
<i>P. nodosa</i> (Pers.) Opiz	Korea, Gyunggi-do, Nov.2004, J.Y. Kim (KH-L1821)
<i>P. orientalis</i> (L.) Spach	Korea, Gyunggi-do, Oct.2003, J.Y. Kim (KH-L798)
<i>P. perfoliata</i> (L.) H. Gross	Korea, Gyunggangbuk-do, Aug.2014, G.H. Gang (KH-L13798)
<i>P. posumbu</i> (Buch.-Ham. ex D. Don) H.Gross	Korea, Gyunggi-do, Oct.2007, J.Y. Kim (KH-L3309)
<i>P. pubescens</i> (Blume) H. Hara	Korea, Gyunggangbuk-do, Oct.2014, G.H. Gang <i>et al.</i> (KH-13817)
<i>P. sagittata</i> (L.) H. Gross	Korea, Gyunggi-do, Oct.2006, J.Y. Kim (KH-L2914)
<i>P. senticosa</i> (Meisn.) H. Gross	Korea, Gyunggangbuk-do, Sep.2012, S.G. Son and H.W.Choi (KH-L10094)
<i>P. thunbergii</i> (Siebold & Zucc.) H. Gross	Korea, Gyunggi-do, Oct.2007, J.Y. Kim (KH-L3380)
<i>P. tinctoria</i> (Aiton) H. Gross	Korea, Gyunggi-do, Oct.2007, J.Y. Kim (KH-L3236)
<i>P. viscofera</i> (Makino) H. Gross	Korea, Gyunggangbuk-do, Aug. 2012, S. G. Son and H.Y. Choi (KH-L10095)
<i>P. viscosa</i> (Buch.-Ham. ex D. Don) H. Gross ex T. Mori	Korea, Gyunggangbuk-do, Sep.2012, S.G. Son and H.S.Kwon (KH-L10096)
<i>P. vulgaris</i> Webb & Moq.	Korea, Gyunggangnam-do, Oct.2012, J.S. Kim (KH-L10059)
Fallopia Adanson	
<i>F. convolvulus</i> (L.) A. Löve	Korea, Gyunggi-do, Nov.2005, J.Y. Kim (KH-L2618)
<i>F. dentatoalata</i> (F. Schmidt) Holub	Korea, Jeollabuk-do, Sep.2013, G.S. Jung and S.J. Kwon (KH-L13170)
<i>F. dumetorum</i> (L.) Holub	Korea, Gyunggi-do, Nov.2005, J.Y. Kim (KH-L2602)
<i>F. japonica</i> (Houtt.) Ronse Decr.	Korea, Gyunggi-do, Nov.2005, J.Y. Kim (KH-L2625)
<i>F. koreana</i> B.U. Oh & J.G. Kim	Korea, Chungcheongbuk-do, Oct.2011, G.Y. Lee (KH-L9470)
<i>F. sachalinensis</i> (F. Schmidt) Ronse Decr.	Korea, Is. Ulleung, Gyunggangbuk-do, Oct.2011, M.S.Kim <i>et al.</i> (KH-L9025)

Table 1 Contd.

Taxon	Voucher specimens
<i>Knorringia</i> (Czukav.) Tzvelev	
<i>K. sibirica</i> (Laxm.) Tzvelev subsp. <i>sibirica</i>	Korea, Incheon, Sep.2006, S.H.Park 61732 (KH)
<i>Polygonum</i> L.	
<i>P. aviculare</i> L.	Korea, Gyunggi-do, Oct.2004, J.Y.Kim (KH-L1772)
<i>Oxyria</i> Hill.	
<i>O. digyna</i> (L.) Hill	D.P.R.K., Mt. Baekdu, Aug.1997, K.W.Park L-61153 (KH)
<i>Rheum</i> L.	
<i>R. rhabarbarum</i> L.	Mongolia, Tariat, Jul.2002, S.H. Park ParkSH23435 (KH);
<i>Rumex</i> L.	
<i>R. acetosa</i> L.	Korea, Gyunggi-do, Jun.2007, J.Y. Kim <i>et al.</i> (KH-3324)
<i>R. acetosella</i> L.	Korea, Gyunggi-do, Jul.2005, J.Y. Kim (KH-L2135)
<i>R. conglomeratus</i> Murray	Korea, Gyungsangnam-do, Jul.2004, J.M. Jung and M.H.Park (KH-1073)
<i>R. crispus</i> L.	Korea, Gyungsangnam-do, Jul.2004, J.M. Jung and J.Y.Kim (KH-L1047)
<i>R. japonicus</i> Houtt.	Korea, Gyunggi-do, Jul.2005, J.Y. Kim (KH-L2126)
<i>R. maritimus</i> L.	Korea, Gangwon-do, Sep.2004, J.M. Jung <i>et al.</i> (KH-L1282)
<i>R. obtusifolius</i> L.	Korea, Gyunggi-do, Jul.2005, J.Y. Kim (KH-L2127)
<i>R. patientia</i> L.	Korea, Chungcheongbuk-do, Jul.2011, E.S. Jeon (KH-L8856)

Herbarium acronyms are in accordance with Thiers (2018) [continuously updated]

(CPD, SPI-13200J-AB). All samples for SEM analysis were coated with platinum using an ion-sputtering device (E-1045; Hitachi, Tokyo, Japan). Samples were examined under a field emission SEM (FE-SEM; S-4700; Hitachi, Tokyo, Japan) operating at 10 kV with a working distance of 10–13 mm. A total of 10 achenes for CPD were measured using the Magnification 2.0 version software (Orbicule, Leuven, Belgium).

We followed the currently accepted taxonomic treatment for the taxa studied to avoid any taxonomic confusion (Freeman and Reveal, 2005; Sanchez *et al.*, 2011). The terminology for fruits and embryos was mainly adopted from Ball *et al.* (1962), Brandbyge (1993), and Ronse Decraene *et al.* (2000).

Results and Discussion

Achene shape, size, colour, embryo type, and micromorphology

Shape: The various achene shapes in Korean Polygonaceae were lenticular, biconvex, trigonous, and spheroidal (Table 2; Fig. 1). Most of the taxa studied had trigonous achenes, and the lenticular shape was observed in five taxa within *Persicaria* (*P. hydropiper*, *P. japonica*, *P. lapathifolia* var. *salicifolia*, *P. nodosa*, and *P. orientalis*; Table 2; Fig. 1F). Biconvex achenes were found in four taxa (*Persicaria filiformis*, *P. nepalensis*, *P. tinctoria*, and *Oxyria digyna*; Table 2; Fig. 1C, D & M), and spheroidal achenes were only observed in *Persicaria perfoliata*.

The longitudinal-section (L.S.) shapes were found to be elliptic (Fig. 2C, O & S), elliptic rhomboid (Fig. 2G & W), ovoid (Fig. 2E, I & K), broadly ovoid (Fig. 2A, Q & U), and circular (Fig. 2M). The cross-section (C.S.) shapes were mostly triangular (Fig. 2B, D, F, H, P, T, V & X), but also sometimes narrowly elliptic (Fig. 2N), elliptic (Fig. 2J), rhombic (Fig. 2R), and triangular- ovoid (Fig. 2L). Most of the taxa studied had a beak (Figs. 1A, B, D, E, F, G, I, J, K, L, N, O, & 2I). Some had a prominent beak, such as a caudate or cuspidate (Fig. 1B, D, E, F, G, I, & J), but five taxa had achenes without a beak (e.g., *Persicaria filiformis*, *P. senticosa*, *P. thunbergii*,

Fallopia dumetorum, *Rheum rhababarum*, *Rumex acetosa*, and *R. acetosella*; Fig. 1C & H). The absence of beak could help to identify some taxa.

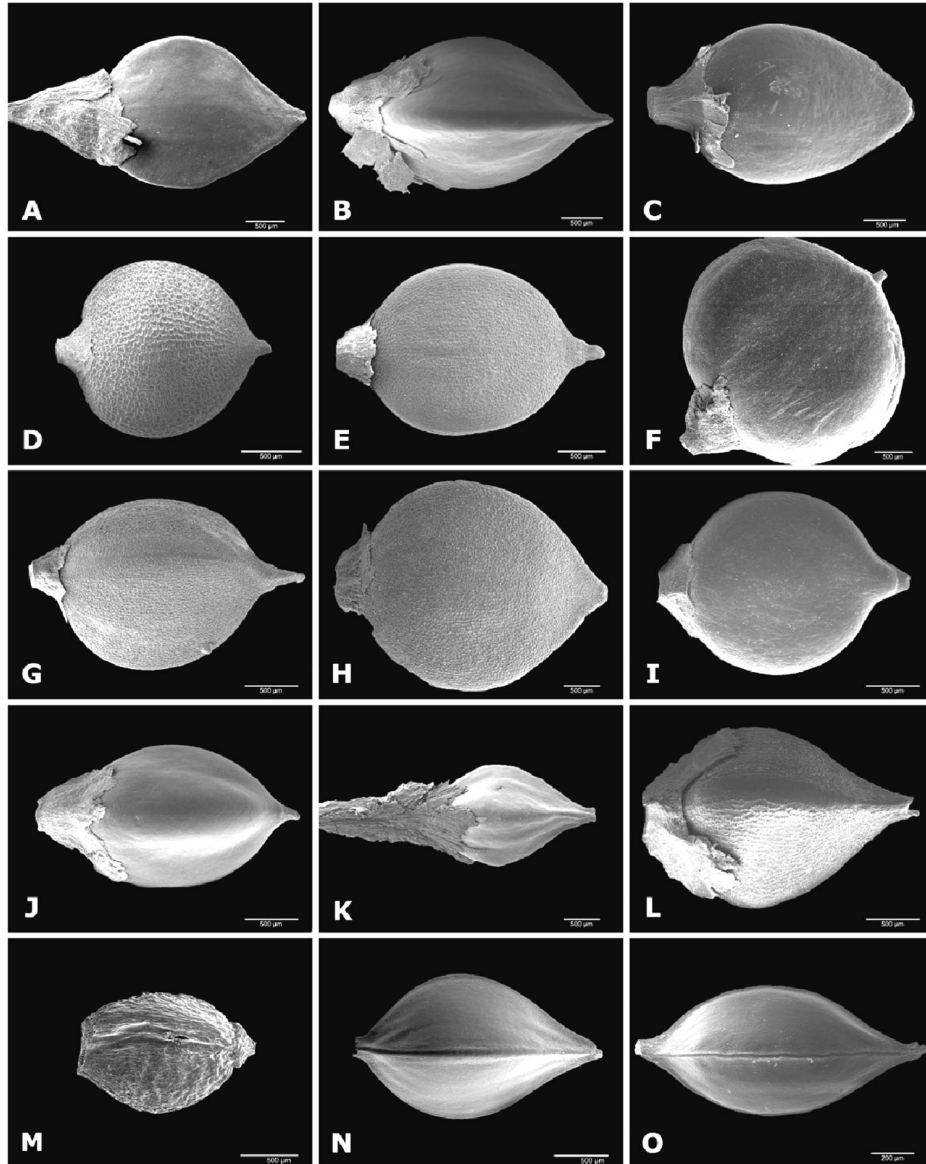


Fig. 1. SEM micrographs of achenes of Polygonaceae in Korea. A. *Aconogonon alpinum*; B. *Bistorta manshuriensis*; C. *Persicaria filiformis* (sect. *Tovara*); D. *Persicaria nepalensis* (sect. *Cephalophilon*); E. *Persicaria maackiana* (sect. *Echinocaluon*); F. *Persicaria orientalis* (sect. *Persicaria*); G. *Persicaria sagittata* (sect. *Echinocaluon*); H. *Persicaria thunbergii* (sect. *Echinocaluon*); I. *Persicaria nodosa* (sect. *Persicaria*); J. *Persicaria pubescens* (sect. *Persicaria*); K. *Fallopia sachalinensis*; L. *Polygonum aviculare*; M. *Oxyria digyna* (beak was broken; see Fig. 2I); N. *Rumex obtusifolius*; O. *Rumex maritimus*.

Table 2. Details of achene characteristics in the Korean Polygonaceae taxa. Infrageneric affiliation (e.g., subgenera or sectional) was obtained from the most accepted taxonomic treatment for the investigated taxa according to Freeman and Reveal (2005) and Sanchez *et al.* (2011).

Taxon	Size range (mm)		Gloss	Colour	Shape	L.S.	C.S.	Beak	Embryo position	Sculpture
	length	width								
Tribe Fagopyreae Yonek.										
Fagopyrum Mill.										
<i>F. esculentum</i> Moench	5.80–6.70	3.90–4.40	-	d.b	trg	ovo	tria	+	folded	smooth
Tribe Persicarieae Dumort.										
Aconogonon (Meisn.) Rechb.										
<i>A. alpinum</i> (All.) Schur	3.79–5.61	2.07–2.77	++	o.b	trg	bov	tria	+	curved	parietal
<i>A. divaricatum</i> (L.) Nakai ex T.Mori	4.24–4.84	2.16–2.98	++	o.b	trg	ovo	tria	+	curved	parietal
Bistorta (L.) Scop.										
<i>B. manshuriensis</i> (Petrov ex Kom.) Kom.	3.17–3.67	2.01–2.23	++	bl	trg	ell	tria	+	curved	parietal
Persicaria (L.) Mill.										
Persicaria sect. Persicaria										
<i>P. hydropper</i> (L.) Delarbre	1.81–2.46	1.35–1.80	+	d.b	lent	bov	nell	+	curved	parietal
<i>P. japonica</i> (Meisn.) Nakai	1.92–2.39	1.35–1.68	+	bl	lent	bov	nell	+	curved	parietal
<i>P. lapathifolia</i> (L.) Delarbre var. <i>lapathifolia</i>	1.77–2.34	1.22–1.47	++	bl	trg	ell	tria	+	curved	parietal
<i>P. lapathifolia</i> var. <i>salicifolia</i> (Sibthorp) Miyabe	2.03–2.85	1.41–1.99	+	d.b	lent	cc	nell	+	curved	parietal
<i>P. longiseta</i> (Brujin) Kitag.	1.76–2.25	1.17–1.46	++	bl	trg	ell	tria	+	curved	parietal
<i>P. nodosa</i> (Pers.) Opiz	2.09–2.61	1.50–1.88	+	d.p.b	lent	bov	nell	+	curved	parietal
<i>P. orientalis</i> (L.) Spach	3.09–3.60	2.63–3.40	+	bl	lent	cc	nell	+	curved	parietal
<i>P. posumbu</i> (Buch.-Ham. ex D.Don) H. Gross	2.43–3.28	1.56–2.06	+	bl	trg	ovo	ell	+	curved	parietal
<i>P. pubescens</i> (Blume) H. Hara	2.16–2.64	1.40–1.71	++	bl	trg	ell	tria	+	curved	parietal
<i>P. tinctoria</i> (Aiton) H. Gross	2.13–2.51	1.10–1.54	++	bl	bicv	ell	rhom	+	curved	parietal
<i>P. viscofera</i> (Makino) H. Gross	1.51–1.86	1.09–1.33	++	bl	trg	ovo	tria	+	curved	parietal
<i>P. viscosa</i> (Buch.-Ham. ex D.Don) H. Gross ex T.Mori	2.54–2.98	1.58–1.97	++	bl	trg	ovo	tria	+	curved	parietal
<i>P. vulgaris</i> Webb & Moq.	1.95–2.54	1.22–1.73	+	d.p.b	trg	ell	tria	+	curved	parietal
Persicaria sect. Cephalophilon (Meisn.) H. Gross										
<i>P. chinensis</i> (L.) H. Gross var. <i>chinensis</i>	2.57–3.41	1.99–2.31	-	bl	trg	bov	tria	+	curved	tubercle wall
<i>P. nepalensis</i> (Meisn.) H. Gross	1.37–2.46	1.25–1.74	-	d.b	bicv	bov	rhom	+	curved	tubercle wall
Persicaria sect. Echinocaulon (Meisn.) H. Gross										
<i>P. dissitiflora</i> (Hemsl.) H. Gross ex T. Mori	3.02–4.00	2.02–2.38	++	d.b	trg	ovo	trov	+	curved	parietal
<i>P. maackiana</i> (Regel) Nakai ex T. Mori	2.52–3.11	1.47–1.94	+	bl	trg	ovo	tria	+	curved	parietal
<i>P. muricata</i> (Meisn.) Nemoto	1.96–2.45	1.20–1.47	++	p.b	trg	ell	tria	+	curved	parietal
<i>P. perfoliata</i> (L.) H. Gross	3.33–4.12	2.83–3.18	++	bl	sph	bov/cc	cc	+	curved	parietal
<i>P. sagittata</i> (L.) H. Gross	2.23–2.73	1.48–1.77	+	bl	trg	ovo	tria	+	curved	parietal
<i>P. senticosa</i> (Meisn.) H. Gross	3.09–3.81	2.38–2.83	-	bl	trg	bov	trov	-	curved	parietal
<i>P. thunbergii</i> (Siebold & Zucc.) H. Gross	3.37–4.25	1.91–2.80	+	br	trg	ovo	trov	-	curved	parietal

Table 2 Contd.

Taxon	Size range (mm)		Gloss	Colour	Shape	L.S.	C.S.	Beak	Embryo position	Sculpture	
	length	width									
<i>Persicaria</i> sect. <i>Tavara</i> (Adanson) H. Gross											
<i>P. filiformis</i> (Thunb.) Nakai	2.78–3.49	1.73–2.01	+	r.b	bicv	bov	rhomb	-	curved	parietal	smooth
Tribe Polygonaceae Rehb.											
Fallopia Adanson											
Fallopia sect. <i>Fallopia</i>											
<i>F. convolvulus</i> (L.) A. Löve	2.73–3.50	1.65–2.03	++	bl	trg	elrh	tria	+	curved	parietal	papillae
<i>F. dentatolata</i> (F. Schmidt) Holub	3.91–5.67	2.21–2.64	++	pu	trg	elrh	tria	+	curved	parietal	smooth
<i>F. dumetorum</i> (L.) Holub	1.37–1.62	0.87–1.09	++	bl	trg	elrh	tria	-	curved	parietal	smooth
<i>Fallopia</i> sect. <i>Reynoutria</i> (Houtt.) Ronse Decker											
<i>F. japonica</i> (Houtt.) Ronse Decker	3.64–5.08	2.34–3.08	++	d.p.b	trg	elrh	tria	+	curved	parietal	shallow papillae
<i>F. koreana</i> B.U. Oh & J.G. Kim	5.13–7.45	2.15–2.64	++	d.p.b	trg	nell	tria	+	curved	parietal	smooth
<i>F. sachalinensis</i> (F. Schmidt) Ronse Decker	2.44–2.98	1.22–1.60	++	bl	trg	elrh	tria	+	curved	parietal	smooth
Knorringia (Czukav.) Tzvelev											
<i>K. sibirica</i> (Laxm.) Tzvelev subsp. <i>sibirica</i>	2.90–3.50	1.90–2.20	++	br	trg	elrh	tria	+	curved	parietal	smooth
Polygonum L.											
Polygonum sect. <i>Polygonum</i>											
<i>P. aviculare</i> L.	2.65–3.13	1.25–1.76	-	br	trg	ovo	trov	+	curved	parietal	tubercle wall
Tribe Rumiceae Dumort.											
Oxyria Hill											
<i>O. digyna</i> (L.) Hill	1.30–2.10	0.80–1.80	-	o.b	bicv	ovo	ell	+	straight	plane	smooth
Rheum L.											
<i>R. rhabarbarum</i> L.	5.00–6.50	4.00–5.20	-	br	trg	bov	tria	-	straight	plane	tubercle wall
Rumex L.											
Rumex subg. <i>Rumex</i>											
<i>R. conglomeratus</i> Murray	1.18–1.58	0.88–1.22	++	d.b	trg	elrh	tria	+	straight	plane	smooth
<i>R. crispus</i> L.	1.88–2.36	1.15–1.53	++	d.b	trg	elrh	tria	+	straight	plane	small pits
<i>R. japonicus</i> Houtt.	1.88–2.23	1.03–1.27	++	o.b	trg	elrh	tria	+	straight	plane	smooth
<i>R. maritimus</i> L.	1.17–1.41	0.60–0.84	++	o.b	trg	ell	tria	+	straight	plane	small pits
<i>R. obtusifolius</i> L.	1.68–2.38	1.03–1.41	++	d.b	trg	elrh	tria	+	straight	plane	small pits
<i>R. patientia</i> L.	2.04–2.78	1.32–1.72	++	d.b	trg	elrh	tria	+	straight	plane	small pits
Rumex subg. <i>Acetosa</i>											
<i>R. acetosa</i> L.	1.51–2.01	0.88–1.15	++	bl	trg	ell	tria	-	straight	plane	smooth
Rumex subg. <i>Acetosella</i>											
<i>R. acetosella</i> L.	1.10–1.41	0.90–1.00	+	d.b	trg	bov	tria	-	curved	plane	small pits

Gloss: +, glossy; ++, strong glossy; -, dull; **Colour:** d.b, dark brown; o.b, orange brown; r.b, red brown; p.b, purple brown; d.p.b, dark purple brown; br, brown; bl, black; pu, purple; **Shape:** C.S., cross-sectioned shape; L.S., longitudinal-sectioned shape; bov, broadly ovoid; bicv, biconvex; cc, circular; elrh, elliptic rhomboid; ell, elliptic; nell, narrowly-elliptic; ovo, ovoid; rhomb, rhombic; sph, spheroidal; trg, trigonous; tria, triangular; trov, trigonous-ovoid; /, or; **Beak:** +, present; -, absent; ~, not applicable.



Fig. 2. Cross and longitudinal section of achenes of Polygonaceae in Korea. A, B. *Aconogonon alpinum* (Type III); C, D. *Bistorta manshuriensis* (Type III); E, F. *Fagopyrum esculentum* (Type I); G, H. *Fallopia dentatoalata* (Type III); I, J. *Oxyria digyna* (Type II); K, L. *Persicaria dissitiflora* (sect. *Echinocaulon*; Type III); M, N. *Persicaria lapathifolia* var. *salicifolia* (sect. *Persicaria*; Type III); O, P. *Persicaria pubescens* (sect. *Persicaria*; Type III); Q, R. *Persicaria tinctoria* (sect. *Persicaria*; Type III); S, T. *Polygonum aviculare* (Type III); U, V. *Rumex acetosella* (Type IV); W, X. *Rumex obtusifolius* (Type II). A, C, E, G, I, K, M, O, Q, S, U, and W, longitudinal section of achenes; B, D, F, H, J, L, N, P, R, T, V, and X, cross-section of achenes in investigated taxa.

The achene shapes of the taxa studied agreed with the descriptions in earlier studies (Ronse Decraene *et al.*, 2000; Li *et al.*, 2003; Freedman and Reveal, 2005; Lee *et al.*, 2010; Kantachot and Chantaranothai, 2011). According to previous studies, some taxa showed heteromorphy in their

achene shape; moreover, collecting season has implications on the achene shape (Yurtseva, 2001; Li *et al.*, 2003; Freedman and Reveal, 2005; Kantachot and Chantaranonthai, 2011). For example, *Persicaria hydropiper* has either convex or trigonous achenes (Lee, 2003; Freedman and Reveal, 2005). The achene shape was consistent for each taxon in present study, however, taxonomic application of achene shape could be needed careful application.

Size: The size of achenes ranged from 1.10–7.45 mm in length and 0.60–5.20 mm in width (Table 2). The large achenes were found on *Fagopyrum esculentum* (5.80–6.70 × 3.90–4.40 mm) and *Rheum rhabarbarum* (5.00–6.50 × 4.00–5.20 mm), whereas the smallest achenes were found in *Rumex maritimus* (1.17–1.41 × 0.60–0.84 mm). The taxa in *Oxyria* and *Rumex* had the small achenes compared to other genera (1.10–2.78 × 0.60–1.80 mm). Most taxa, except *Fagopyrum esculentum*, *Rheum rhabarbarum*, *Rumex acetosella* and *R. maritimus*, showed to have similar size ranges of achenes (1.37–5.67 × 0.87–3.40 mm). The achene sizes in the taxa studied were also similar to those recorded in earlier studies (Li *et al.*, 2003; Kantachot and Chantaranonthai, 2011). The largest or smallest achene sizes could be used to classify to the genus level.

Colour: Fully matured achenes of most of the taxa were brownish to black, and dull or shiny (Table 2); this colour is commonly found in Polygonaceae (Kantachot and Chantaranonthai, 2011). The colour of fully matured fruit is usually not an important character to identify genus or species, except for in a few taxa that have odd colours such as grey or greyish green (Kantachot and Chantaranonthai, 2011; Sadeghian *et al.*, 2014). Most of the taxa studied had glossy achenes except six examined taxa (Table 2), which had dull achenes (e.g. *Fagopyrum esculentum*, *Oxyria digyna*, *Persicaria nepalensis*, *P. senticosa*, *Polygonum aviculare*, and *Rheum rhabarbarum*). The existence of dull achenes is useful for the identification of the species.

Embryo shape and position: Three embryo shapes were observed in this study, *viz.* curved, straight, and folded (Table 2; Fig. 2). Most taxa studied had curved embryos (e.g. *Aconogonon*, *Bistorta*, *Fagopyrum*, *Fallopia*, *Knorringia*, *Persicaria*, and *Polygonum*; Fig. 2A, C, G, K, M, O, Q, S & U). While *Oxyria*, *Rheum*, and *Rumex* (except *R. acetosella*) had straight embryos (Fig. 2I & W), and folded embryos were only observed in *Fagopyrum* (Fig. 2E & F). The embryo shapes of the taxa studied were similar to those in previously published data (Martin, 1946; Brandbyge, 1993; Freedman and Reveal, 2005; Sanchez *et al.*, 2011). In the present study, all taxa studied had one shape of embryo; however, embryos of Rumiceae were observed to be curved or straight (Freedman and Reveal, 2005). In this study, *Rumex acetocella* of the *Rumex* subg. *Acetosella* had a different shape from other Rumiceae taxa. Additionally, two types of embryo position (plane and parietal) were observed (Table 2; Fig. 2). Most of the taxa had aparietal position (Fig. 2B, D, H, J, L, N, P, R & T), while *Oxyria*, *Rheum*, and *Rumex*, which belong to the tribe Rumiceae, had a plane-positioned embryo (Fig. 2V & X).

The embryos can be divided into four types based on shape and position: Type I – folded embryo (*Fagopyrum* - Fagopyreae); Type II – straight embryo with plane position (*Oxyria*, *Rheum*, and *Rumex* - Rumiceae); Type III – curved embryo with parietal position (*Aconogonon*, *Bistorta*, *Persicaria*, *Fallopia*, *Knorringia*, and *Polygonum* - Persicarieae and Polygoneae); Type IV – curved embryo with plane position (*Rumex acetosella*). The types are congruent with the delimitation of suggested tribes (Sanchez *et al.*, 2011; Fig. 4). For example, the Type I embryo, which is an unusual type in Polygonoideae, was found only in *Fagopyrum*. This genus which was separated into the tribe Fagopyreae according to the recent taxonomic system (Sanchez *et al.*, 2011), and its embryo type could be considered to be an apomorphy (Fig. 4). The Persicarieae and Polygoneae both show Type III embryos, which could be assumed to be a parallelism of characteristics when compared with current phylogenetic studies (Fig. 4). The tribe Rumiceae is strongly supported by embryo position; however, embryo shape was varied at generic level.

Achene micromorphology: Four types of achene surfaces were recognized: smooth, papillae, tuberculate, and small pits (Table 2; Fig. 3). Most taxa had smooth to rugose surfaces without appendages (Fig. 3A, B, H & M). These types had remarkable anticlinal cell walls, generally undulated, and of these, *Fagopyrum esculentum* was characterized by longitudinal grooves on the achene surface (Fig. 3C).

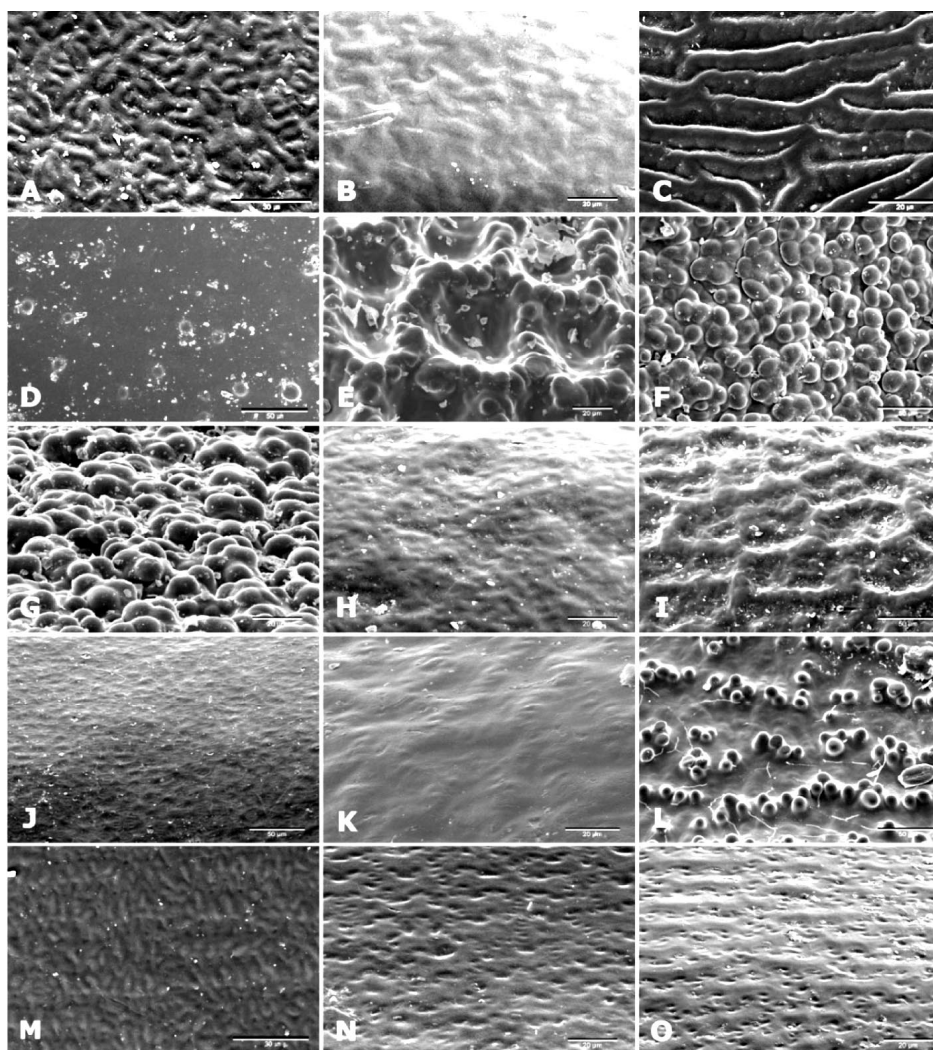


Fig. 3. The surface of achenes of Polygonaceae in Korea. A. *Aconogonon alpinum* (smooth); B. *Bistorta manshuriensis* (smooth); C. *Fagopyrum esculentum* (smooth); D. *Fallopia convolvulus* (papillae distributed irregularly); E. *Persicaria nepalensis* (sect. *Cephalophilon*; tubercles along the anticlinal cell walls); F. *Persicaria maackiana* (sect. *Echinocaulon*; tubercles distributed throughout entire pericarp); G. *Persicaria sagittata* (sect. *Echinocaulon*; tubercles distributed throughout entire pericarp); H. *Persicaria nodosa* (sect. *Persicaria*; smooth); I. *Persicaria posumbu* (sect. *Persicaria*; tubercles along the anticlinal cell walls); J. *Persicaria pubescens* (sect. *Persicaria*; shallow papillae); K. *Fallopia japonica* (shallow papillae); L. *Polygonum aviculare* (discontinued tubercles along the anticlinal cell walls); M. *Rumex acetosa* (smooth); N. *Rumex crispus* (small pits); O. *Rumex obtusifolius* (small pits).

Tubercles or papillae were divided into two types based on their distribution patterns: Type (i), covered the entire achene (Fig. 3E & F), and Type (ii), distributed along the anticlinal cell walls (Fig. 3E, I, J, K & L). Type (i) tubercles were observed in three taxa of *Persicaria*, and they were densely or regularly distributed (*P. maackiana*, *P. sagittata*, and *P. senticosa*; Fig. 3F & G). Type (i) papillae were only observed in *Fallopia convolvulus* (Fig. 3D; Table 2), and were loosely and irregularly distributed compared to the tubercles. Type (ii) tubercles were observed in four taxa (*Persicaria nepalensis*, *P. posumbu*, *Polygonum aviculare*, and *Rheum rhabarbarum*; Fig. 3E, I, J & L). Type (ii) tubercles of three taxa showed continuous distribution and were arranged along the anticlinal cell wall (Fig. 3E, I & J), while those of *Polygonum aviculare* showed a discontinuous arrangement (Fig. 3L). Similarly, Type (ii) papillae were observed in three taxa of *Persicaria* (*P. lapathifolia* var. *lapathifolia*, *P. pubescens*, and *P. vulgaris*; Fig. 3K), but these structures were represented by collapsed anticlinal cell walls (Ronse Decrane *et al.*, 2000). Yurtseva (2001) suggested that the xerophytic taxa of *Polygonum* subsect. *Polygonum* usually had verrucae on the achene surface, while the taxa that inhabit wet environments did not. Although the functions of these verrucae are not clear, smooth and glossy surface increase water repellency and prevent fungal or pathogenic infection (Barthlott, 1981; Yurtseva, 2001). Thus, the verrucae could be related to water absorption. In the present study, some taxa without tubercles or papillae within other genera were distributed through wet valleys (e.g., *Persicaria muricata*); thus this is seemed to support the early suggestion. While there are also taxa which inhabit both environments (e.g., *Persicaria senticosa* also inhabit wet valleys; Li *et al.*, 2003; Freedman and Reveal, 2005).

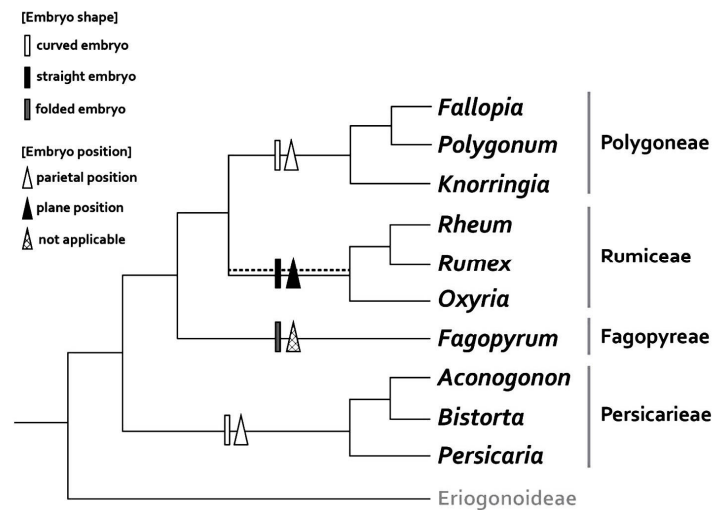


Fig. 4. Diagrams of embryo characters on most recent cladograms. Simplified phylogenetic tree is adopted from Schuster *et al.* (2015). Embryo shape was described as rectangular, and embryo position was described as triangular. The dotted line means that various type of embryo shape were observed in this group compared to those found in early studies (e.g., Freedman and Reveal, 2005; Sanchez *et al.*, 2011).

Small pits were observed to be scattered on the surface of most *Rumex* taxa (*R. acetosella*, *R. crispus*, *R. maritimus*, *R. obtusifolius*, and *R. patientia*; Table 2; Fig. 3N & O). According to a previous study, the small pits were also found in the *Persicaria* sect. *Tovara* (investigated taxa: *P. neofiliformis* and *P. virginiana*; Ronse Decrane *et al.*, 2000); however, the *Persicaria* sect. *Tovara* (*P. filiformis*) used in this study had a smooth surface (Table 2). This difference in surface sculpture could be considered to be interspecies difference.

Taxonomic implication of achene morphology in Korean Polygonaceae

The taxonomic position of *Aconogonon* has been controversial. The *Aconogonon* was usually acknowledged to be an independent genus although it was belonged to *Polygonum s.l.* in early studies (Hedberg, 1946; Haraldson, 1978; Freedman and Reveal, 2005). The sister group of the *Koenigia* with *Aconogonon* is *Bistorta*. In comparison with achene morphology, almost all characteristics, such as the shape, size, existence of beak, glossy, embryo and smooth surface, are similar between *Aconogonon* and *Bistorta*. The genus *Koenigia* in previous study had also same embryo type and smooth surface as in *Aconogonon* and *Bistorta*; however, the achene is distinguished from *Aconogonon*–*Bistorta* based on the lack of beak, glossiness and smaller size (cf., $1.10\text{--}1.84 \times 1.79\text{--}1.02$ mm; Ronse Decrane *et al.*, 2000; Kong and Hong, in prep.).

Persicaria lapathifolia var. *lapathifolia* is complicated taxonomically, thus many taxa were treated as synonyms of this taxon (e.g., Freedman and Reveal, 2005; Chang *et al.*, 2014). For example, *P. lapathifolia* var. *salicifolia* and *P. nodosa*, were treated as synonyms of *P. lapathifolia* var. *lapathifolia* (Freedman and Reveal, 2005; Chang *et al.*, 2014), or only one of them was treated as synonym (Timson, 1963). Li *et al.* (2003) suggested that *P. lapathifolia* var. *salicifolia* was admitted independent variety of *P. lapathifolia* var. *salicifolia*. The achene morphological characteristics between *P. lapathifolia* var. *salicifolia* and *P. nodosa* appeared to be more similar rather than those between *P. lapathifolia* var. *salicifolia* and *P. lapathifolia* var. *lapathifolia* (Table 2). Thus, *P. lapathifolia* var. *lapathifolia* and *P. lapathifolia* var. *salicifolia* could be separated as independent variety from each other, although the taxonomic position of *P. nodosa* is still unclear based on its achene characteristics.

In conclusion, achene morphological characteristics are useful to recognize certain taxa to the species, generic, or tribal level. Of the studied characteristics, the surface micromorphology of achene or embryo characteristics are rather consistent at the generic or tribal level; for example, small pits were found in most *Rumex* taxa, and papillae were only found in *Fallopia convolvulus*. In addition, the comprehensive consideration of achene characteristics are more useful to identify at the species level; for example, dull, broadly ovoid, biconvex and achenes with tubercle walls are characteristics of *P. nepalensis*, and regularly tuberculate on the whole achene surface and straight embryo in the plane position (Type IV) are characteristics of *Rumex acetosella*. This achene morphological study could improve our understanding of Korean Polygonaceae. A comparative study with molecular phylogeny will further improve our understanding of systematic tendencies in these groups.

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