Karyologic and Heterosis Studies of the Artificial Inter- and Intraspecific Hybrids of Viola ×wittrockiana and Viola cornuta

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Abstract. An artificial crossing was made between four Viola ×wittrockiana (2n = 48) lines and one Viola cornuta inbred (2n = 26) line as well as among V. ×wittrockiana lines to investigate the cytologic characteristics, fertility, and heteroses of hybrids. The sizes of flowers and stomata and the leaf areas of the V. ×wittrockiana plants were larger than those of the V. cornuta plants. The karyologic stability of V. cornuta was greater than that of V. ×wittrockiana, and ≈20% of individuals in the latter deviated from the given 2n = 48. Capsule setting after interspersed hand pollination ranged from 28% to 94%, and F1 seed germination ranged from 16% to 88%, revealing no obvious pre- or postzygotic selection mechanisms. The chromosome numbers in V. ×wittrockiana × V. cornuta F1 seedlings varied (2n = 34–38), with about half the cells exhibiting the intermediate (2n = 36) value. These interspecific hybrids exhibited positive heterosis in flower size (range, 11% to 66%) and negative heterosis in plant height (range, –12% to –57%). Both of these traits are desirable in pansy breeding programs.

Breeding methods for ornamental plants range from traditional selection breeding programs to modern biotechnological and genetic engineering methods. Many ornamental plants, including geraniums, impatiens, begonias, and primulas, originated from interspecific and intergeneric crosses, which leads to a high degree of heterozygosity in the resulting hybrids, with polyploidy and aneuploidy often occurring. In seed-propagated ornamentals with a considerable seed market, cultivars will normally be bred as hybrids based on inbred parental lines. The main emphasis in ornamental plant breeding is to improve the variety traits, novel color, form, size, number of flowers, flower vase life, repeat blooming, disease resistance, nutrient uptake capacity, and growth habits (De, 2017). Commercially available pansies are F1 hybrids produced by hand crossing. Currently, such production of Viola tricolor maxima with hermaphrodite flowers requiring emasculation occasionally occurs at the expense of limited profitability (De, 2017; Reimann-Philipp, 1983).

Heterosis is a phenomenon whereby the phenotype of F1 hybrids is superior to that of their parents. Intralocus interactions between alleles, complementation of dominant alleles, or interloci epistatic interactions are genetic mechanisms that may cause nonadditive phenotypic inheritance in hybrids. However, different views exist on what portion of the heterotic variation is modulated by each of these mechanisms (Fridman, 2015).

Viola ×wittrockiana Gams ex Kappert., known as garden pansy, is one of the most common bedding plants worldwide, exhibiting rich flower colors, cold tolerance, and other charming characteristics, such as odor and taste (Fernandes et al., 2017; Lagibo et al., 2005; Li et al., 2014, and literature cited therein). This species is also studied as a promising source of natural antioxidants (Vukics et al., 2008). Present-day garden pansies are horticultural hybrids rather than a natural species. Initially, the species was selected as an interspecific hybrid resulting from the crossing of Viola L. sect. Melančium Ging. species (pansies), V. tricolor L., V. lutea Hudson, and V. altaica Ker-Gawler (Kroon, 1972). The species differs from wild pansies based on the absence of dark lines on the flower petals (nectar guides for pollinators) and the presence of huge blocks of color on the lower (anterior) and lateral petals called a “face.” This pansy and its progeny have become popular with gardeners and breeders throughout Europe. At the turn of the 20th century, Charles Stewart bred clear color pansies without faces that were welcomed by North American gardeners. Currently, V. ×wittrockiana is one of the dominant hybrids among ornamental bedding plants in the U.S. market (Janick, 1998).

During the past 60 years, much of the innovative pansy breeding has been performed in Germany, the United States, and Japan (Zhang et al., 2010). New pansy varieties with different colors, such as shades of pink, rose, or orange, and unusual bicolor designs have been introduced and are available to gardeners. Studies using a simple selection method to reduce the ploidy level by crossing with diploids to improve uniformity, as well as an increase of polyploidy by mutagenesis to maximize plant morphologic and physiologic characters, have already been performed (Dalbato et al., 2013; Kroon, 1972; Lagibo et al., 2005). Lagibo et al. (2005) demonstrated the positive influence of increased polyploid level on frost tolerance and winter survival of garden pansy.

Along with the increasing popularity of pansy cultivation worldwide, breeding goals continue to develop. Recently, V. cornuta L. (homed pansy) has been crossed successfully with V. ×wittrockiana for the creation of new desirable phenotypic traits, such as increased flowering, plant compactness, and tolerance to environmental stresses (Li, 2010; Liu, 2008; Zhang and Gu, 2009). Currently, some hybrid cultivars of these two species—e.g., ‘Nature Series’ and ‘Power Mini’—are bred by the Japanese seed company Takii Seed (Kyoto, Japan) and Sakata Seed (Japan) respectively. To meet the ever-growing expectations of customers (practical approach) and to increase the predictability of the crossing treatments (basic science approach), we adopted four inbred lines of V. ×wittrockiana and one inbred line of V. cornuta to investigate the cytologic basis of hybridization and heterosis in their hybrids.

Materials and Methods

Derivation of inbred lines of V. ×wittrockiana and V. cornuta and their morpho-anatomic description. The breeding experiments were performed in the garden field of the Henan Institute of Science and Technology (Xinxiang, China) from 2015 to 2017. Four V. ×wittrockiana inbred lines and one V. cornuta inbred line (Table 1: Fig. 1A–E) were generated from commercially available seeds by self-crossing for five or six generations, given accession numbers, and used as parental lines. Plants were grown in a closed plastic
Table 1. The pedigrees, accession numbers, and origins of *Viola cornuta* and *Viola ×wittrockiana* lines used for inter- and intraspecific crosses.

| No. | Name           | Pedigree                  | Species               | Origin          |
|-----|----------------|---------------------------|-----------------------|-----------------|
| 1   | JB-1-1-2       | Inbred line derived       | *V. cornuta*          | Goldsmith seed  |
|     |                | from Penny Blue           |                       |                 |
| 2   | DFM-11-2-1     | Inbred line derived       | *V. ×wittrockiana*    | Gartenland GmbH |
|     |                | from Frühblühende Mischung| Aschersleben          |                 |
| 3   | DFM-11-1-3     | Inbred line derived       | *V. ×wittrockiana*    | Gartenland GmbH |
|     |                | from Frühblühende Mischung| Aschersleben          |                 |
| 4   | DFM-8-4-3      | Inbred line derived       | *V. ×wittrockiana*    | Gartenland GmbH |
|     |                | from Frühblühende Mischung| Aschersleben          |                 |
| 5   | XXL-YB-1-1-1-1 | Inbred line derived from  | *V. ×wittrockiana*    | PanAmerican seed |
|     |                | extra flower size         |                       |                 |

Artificial crossing of inbred lines of *V. cornuta* and *V. ×wittrockiana* to obtain *F₁* progeny. Our artificial crossing design among five inbred lines adopted Griffing’s method III of a complete diallelic cross (Griffing, 1956). Flower buds to be opened the next day were chosen and isolated with sulfuric acid paper bags and labeled immediately. One week later, the isolation bags were removed from the enlarged ovaries, and plants were housed under insect nets to avoid any repeated pollinations, which are possible in pansies as a result of stigma receptivity longer than 1 week (Miyajima, 2006). One month after crossing, mature capsules were collected, and the capsule settings were counted with respect to undeveloped ovaries. Five to six flowers per plant were emasculated and pollinated. A total of 24 plants were pollinated in *V. cornuta × V. ×wittrockiana* and 36 plants in *V. ×wittrockiana × V. ×wittrockiana*.

*F₁* germination and morphologic characteristics (heterosis). In Oct. 2016, selected, mature, well-developed seeds of the crosses and of parental plants were sowed in individual pots of planting trays filled with a peat-vermiculite ratio (v/v) of 2:1 and were maintained in plastic chambers. Seeds were watered regularly. Two weeks after sowing, the number of germinated hybrid seeds was counted. Only those seedlings that were germinated 2 weeks after cultivation were taken into further consideration. The number of germinated hybrid seeds was counted. Only those seedlings that were germinated 2 weeks after cultivation were taken into further consideration. The seedlings of inbred lines of *V. ×wittrockiana* and *V. cornuta* and crossings were transplanted into 10-cm (diameter) × 10-cm (high) pots when they exhibited two to three true leaves. Plants were transplanted into the field in Mar. 2017, and were maintained for further growth and blossoming (Fig. 1F). Ten randomly selected plants of each accession were chosen in Apr. 2017 to investigate plant height, plant spread (width), flower number and size (height), flower shape (height–width ratio), leaf shape (length–width ratio), and area. A fully developed leaf and an open flower were measured per plant. Mid-parent heterosis of these characters was calculated according to the Eq. 100\(\frac{(P_1 + P_2)/2}{(P_1 + P_2)/2}\) (Marame et al., 2009).

Chromosome counting in inbred lines and their *F₁* hybrid progeny. The seeds of inbred lines and their *F₁* progeny were germinated on filter paper soaked with distilled water at room temperature. Roots 1 to 2 cm in length were sampled, and their root tips were dissected under a stereomicroscope. The seedlings were pretreated for 24 h at 0 °C and fixed in a mixture of glacial acetic acid and absolute ethanol (3:1 ratio, v/v) for 24 h. The fixed root tips were then macerated with 1 mol L⁻¹ hydrochloric acid at 60 °C for 6 to 8 min. Finally, the material was stained with carbol fuchsin, flattened with a cover slip, and observed under a Nikon Eclipse 80i microscope (Nikon Corporation) with a magnification of 10 (eye lens) × 100 (field lens). The images were generated using CellSens (ver. 1.12) Imaging Software (Olympus Corporation, Tokyo, Japan). At least 30 plates from 10 plants per accession were observed.

Results

Morpho-anatomic and cytologic characteristics of the inbred lines of *V. cornuta* and *V. ×wittrockiana*. Stomata length, stomata width, leaf area, and flower size of the *V. cornuta* inbred line (118.1 \(\mu\)m, 70.0 \(\mu\)m, 2.5 cm², and 2.1 cm, respectively) were reduced significantly compared with those of the *V. ×wittrockiana* inbred lines (range, 140.4–174.1 \(\mu\)m, 85.4–116.2 \(\mu\)m, 4.4–8.4 cm², and 3.5–5.8 cm, respectively) (Table 2). The *V. cornuta* inbred line exhibited increased stomatal density compared with *V. ×wittrockiana* inbred lines, but the leaf and flower shapes did not differ significantly between the *V. cornuta* inbred line and the *V. ×wittrockiana* inbred lines (Table 2). The *V. cornuta* line (JB-1-1-2) was consistently 2\(n\) = 26 in all investigated plants (Fig. 2A). More than 80% of plants in each inbred line of *V. ×wittrockiana* were 2\(n\) = 48 (Fig. 2B–E). The remaining plants were 2\(n\) = 44–46 (Fig. 2F–H). No intraindividual variability in chromosome number in inbred lines of either species was observed.

Capsule setting after inter- and intraspecific artificial pollination and seed germination of *F₁* hybrids. Some obstacles, both prezygotic and postzygotic, are typically encountered in interspecific crossing, such as pollen–stigma incompatibility and hybrid embryo abortion. Even if these obstacles are overcome, *F₁* interspecific hybrids can exhibit reduced fertility, which can measured as reduced seed setting and germination. The percentage of capsule setting after interspecific crossing ranged from 28% to 94% and from 18% to
The chromosome number in F1 hybrids among inter- and intraspecific artificial diversity in chromosome number was noted. The most frequent value was 2n = 48, whereas that in the hybrids of V. wittrockiana and V. cornuta inbred lines. The euploid metaphase plates of V. cornuta (n = 46). DFM-8-4-3 (2n = 48), (D) DFM-8-4-3 (2n = 48), (E) XXL-YB-1-1-1-1 (2n = 48), (F) XXL-YB-1-1-1-1 (2n = 44), (G) DFM-11-1-3 (2n = 45), and (H) DFM-11-2-1 (2n = 46).

90% after intraspecific crossing (Table 3). The percentages of seed germination ranged from 16% to 88% for the F1 hybrids of V. ×wittrockiana × V. cornuta and from 9% to 98% for V. ×wittrockiana × V. ×wittrockiana. The differences in the percentages of capsule setting and seed germination were reflected mainly in crossing direction rather than between interspecies or intraspecies (Table 3).

Variation in chromosome numbers of intra- and interspecific F1 hybrids. High diversity in chromosome number was noted among inter- and intraspecific artificial hybrids. The chromosome number in F1 hybrids between V. cornuta and V. ×wittrockiana was 2n = 34–38, whereas that in the hybrids between inbred lines of V. ×wittrockiana was 2n = 39–48 (Fig. 3). Both intra- and interindividual variability in chromosome number were observed. However, the most frequent chromosome numbers were close to the middle value of the chromosome number ranges. The most frequent value was 2n = 36 (49.4% of cells) for interspecific crossing and 2n = 46 (43.3% of cells) for intraspecific crossing. The percentage of cells with extreme values was relatively low (Figs. 3 and 4).

Heterosis of inter- and intraspecific F1 hybrids. Hybrids typically exhibit heterosis in plant vigor and tolerance to environmental conditions. The inter- and intraspecific F1 hybrids in this study exhibited various heteroses with respect to different characters. We chose to analyze those characters that were the most discriminative for the two species (leaf area and flower size) and those characters most desired by breeders (e.g., flower number, plant height). With regard to flower size, all the F1 hybrids yielded positive heterosis, with interspecific hybrids varying from 11% to 66% (flower size range, 3.3–6.4 cm) and intraspecific hybrids varying from 23% to 75% (flower size range, 4.3–7.6 cm). The hybrids became shorter, yielding negative heterosis in interspecific hybrids (from ~12% to ~57%) and in intraspecific hybrids (from ~15% to ~42%) compared with parental lines. The leaf area and plant width of the hybrids displayed significant positive or negative heterosis depending on crossed lines and the direction of crossing. With regard to flower number, interspecific hybrids exhibited positive heterosis when V. cornuta served as the male parent but negative heterosis when V. wittrockiana served as the female parent. Most intraspecific hybrids exhibited negative heterosis in flower number (Table 3).

Discussion

Based on cytologic and molecular analyses, most pansies from the section Melanium originate from hybridization events leading to explosive, rapid reticulate radiation (Ko et al., 1998; Yockteng et al., 2003). High genetic similarity and the lack of interspecific barriers ensure the generation of fertile hybrids with only slightly reduced pollen viability, even between species at different ploidy levels (Slomka et al., 2018). In addition, our results support this claim given that the frequency of capsule setting after interspecies crossing and seed germination of F1 hybrids was generally high. The revealed differences resulted mostly from crossing combination and direction.

The current large-flowered garden pansy (V. ×wittrockiana) originated from a cross between V. tricolor (n = 13), V. lutea (n = 24), and V. altaica (n = 11) (Kroon, 1972). The chromosome number of the majority of pansy varieties is 2n = 48 according to Horn (1956), whereas Kroon (1972) reported 2n = 52 in the group Hollandse Reuzen (Hemelsblauw, Goudgeel, Witt). All of the inbred lines of V. ×wittrockiana in our study were 2n = 48. In general, garden pansies with 48 chromosomes are commonly recognized as octoploid, with x = 6 as the base chromosome number (Ajalin et al., 2002), whereas V. cornuta have x = 13. This value is different from earlier counts demonstrating x = 11 (Marcussen et al., 2010, and literature cited therein), which could be recognized as diploid. However, this chromosome number seems to be secondary. Clausen (1927) argued that the genome of 13 chromosomes is not primary for V. tricolor. Early cytotaxonomic articles postulated x = 11 or x = 5 (Clausen, 1931), whereas the most recent phylogenetic studies indicate x = 7 (Yockteng et al., 2003) and x = 12 (Marcussen et al., 2015) as the base chromosome number for the Melanium section.

A crossing between V. ×wittrockiana and V. cornuta should, theoretically, yield plants with 2n = 37. In fact, the majority of cells were 2n = 36; however, this number deviated in both directions and ranged from 34 to 38. The variability of hybrid derivatives within such a broad range of chromosome numbers, including those with odd numbers, is not rare in pansies and was described in several species (Krahulcová et al., 1996, and literature cited therein). In our experiment, only F1 progeny were analyzed, and these progenies typically exhibit increased chromosome variability compared with the following generations of hybrids. However, the relatively high karyologic stability of F1 is a good prognosis for future breeding treatments of these plants. The variability in chromosome number in interspecific hybrids may result from the karyologic variability of V. ×wittrockiana (~20% of plants with chromosome numbers other than 2n = 48) and/or from incomplete genomic stability of one or two parental species. As an indicator of regular meioosis and genome stability, pollen viability results indicate that the garden pansy exhibits a less stable genome compared with...
Table 3. Capsule setting in inbred lines of *Viola cornuta* and after artificial intra- and interspecies crossing and seed germination, phenotype parameters, and heterosis of F1 intra- and interspecific hybrids.

| Direction of crossing | Capsule setting (setting %) | Plant size (cm) | No. of flowers | Heterosis | Heterosis setting (%) | Leaf area (cm²) | Flower size (ht) | Flower shape (ht/width) | Plant ht (cm) | Plant spread (width) (cm) | No. of flowers |
|-----------------------|-----------------------------|----------------|---------------|-----------|-----------------------|----------------|----------------|-----------------------|----------------|---------------------------|---------------|
| **V. cornuta × V. wittrockiana** | 1 | 18 (20, 30) | 30 (25, 40) | 20 | 1.2 (1.1, 1.3) | 4.0 (3.9, 4.2) | 5 | 4.2 (4.1, 4.3) | 47 | 1.1 (1.1, 1.1) | 9 | 12.0 (10.0, 13.0) | –20 |
| | 2 | 60 (50, 70) | 51 (41, 55) | 33 | 1.6 (1.6, 2.3) | 5.1 (4.9, 5.3) | 32 | 4.1 (4.1, 4.2) | 47 | 1.1 (1.1, 1.1) | 3 | 11.0 (10.0, 12.0) | –20 |
| | 3 | 28 (20, 30) | 42 (40, 53) | 14 | 1.6 (1.1, 1.7) | 4.0 (3.8, 4.3) | –14 | 3.8 (3.7, 4.1) | 32 | 1.1 (1.1, 1.1) | 4 | 11.0 (8.5, 14.0) | –34 |
| **V. cornuta × V. wittrockiana** | 1 | 12 (20, 30) | 30 (25, 40) | 20 | 1.2 (1.1, 1.3) | 4.0 (3.9, 4.2) | 5 | 4.2 (4.1, 4.3) | 47 | 1.1 (1.1, 1.1) | 9 | 12.0 (10.0, 13.0) | –20 |
| | 2 | 60 (50, 70) | 51 (41, 55) | 33 | 1.6 (1.6, 2.3) | 5.1 (4.9, 5.3) | 32 | 4.1 (4.1, 4.2) | 47 | 1.1 (1.1, 1.1) | 3 | 11.0 (10.0, 12.0) | –20 |
| | 3 | 28 (20, 30) | 42 (40, 53) | 14 | 1.6 (1.1, 1.7) | 4.0 (3.8, 4.3) | –14 | 3.8 (3.7, 4.1) | 32 | 1.1 (1.1, 1.1) | 4 | 11.0 (8.5, 14.0) | –34 |

* x denotes the median value recorded for that trait, y is the smallest value, and z is the largest value.
Fig. 3. The distribution of chromosome numbers in cells of interspecific hybrids between \textit{Viola xwittrockiana} and \textit{Viola cornuta} (\(V.C \times V.W, V.W \times V.C\)) and intraspecific hybrids between \textit{V. xwittrockiana} lines (\(V.W \times V.W\)).

Fig. 4. (A–F) The selected metaphase plates of hybrids between \textit{Viola xwittrockiana} and \textit{Viola cornuta} inbred lines. (G–P) The selected metaphase plates of hybrids between \textit{V. xwittrockiana} inbred lines. Original magnification was 10×100, and the image was generated using CellSens (ver. 1.12) Imaging Software (Olympus Corporation, Tokyo, Japan). (A) \(1 \times 2 (2n = 36)\), (B) \(2 \times 1 (2n = 36)\), (C) \(1 \times 3 (2n = 34)\), (D) \(3 \times 1 (2n = 36)\), (E) \(1 \times 4 (2n = 35)\), (F) \(1 \times 5 (2n = 36)\), (G) \(2 \times 3 (2n = 44)\), (H) \(3 \times 2 (2n = 46)\), (I) \(2 \times 4 (2n = 44)\), (J) \(4 \times 2 (2n = 46)\), (K) \(2 \times 5 (2n = 46)\), (L) \(3 \times 4 (2n = 46)\), (M) \(3 \times 5 (2n = 46)\), (N) \(5 \times 3 (2n = 45)\), (O) \(4 \times 5 (2n = 46)\), and (P) \(5 \times 4 (2n = 39)\).

Further study, including block design and season/space replications, to eliminate environmental effects and to open up new possibilities for pansy breeding programs. Although seeds of \textit{V. xwilliamsii} (described as a hybrid between \textit{V. cornuta} and \textit{V. xwittrockiana}) are commercially available, basic and applied knowledge of this ornamental plant was not known before this study.

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