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Article

Selection of Urban Trees to Enhance Pollinator Food Resources: Comprehensive Consideration of Various Factors for Productivity Comparison

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Abstract: The decline in global pollinator populations has raised serious concerns about the sustainability of ecosystems and agricultural productivity. Urban environments, often characterized by habitat loss and environmental stressors, are considered challenging habitats for pollinators. However, urban green spaces, including street and ornamental trees, can play a crucial role in supporting pollinators by providing essential food resources. This study aimed to evaluate the sugar and amino acid production of eight urban tree species to determine their potential contributions to pollinator nutrition. Our findings revealed significant variability among species regarding nectar volume, sugar content, and amino acid composition, emphasizing the importance of considering multiple factors when assessing the utility of floral resources. Consequently, *Tilia amurensis*, *Heptacodium miconioides*, *Aesculus turbinata*, and *Wisteria floribunda* demonstrated superior potential in supporting urban pollinator communities. Contrastingly, *Sorbus commixta*, *Styrax japonicus*, and *Cornus kousa*, often favored for their aesthetic appeal, showed less potential. This study underscores the need for urban tree selection that prioritizes species that provide diverse and abundant nutritional resources for pollinators while balancing aesthetic and ecological values. Our results offer a foundation for better-informed urban biodiversity management and contribute to creating pollinator-friendly urban environments.

Keywords: urban tree; floral resource; availability; sugar yield; amino acid composition

1. Introduction

Plant–pollinator interactions are essential for the survival of both parties [1,2]. The transfer of pollen by pollinators contributes to seed production and the maintenance of genetic diversity in flowering and entomophilous plants. Pollinators utilize the nectar and/or pollen collected from plants as nutritional resources, which are vital for the growth, development, and immune system maintenance of their colonies and individuals [3].

In recent years, a decline in pollinators has been reported in many countries [4–6]. This decline is believed to be caused by stressors such as habitat loss, parasites and diseases, pesticides, lack of flowers and monotonous diets, competition, and climate change, which may act alone or in combination, thereby exacerbating the situation [7]. The reduction in the abundance and diversity of pollinators threatens ecosystem sustainability [8] and can decrease agricultural crop production, posing risks to food security [9]. Consequently, the importance of pollinators is being increasingly recognized today.

Urban areas are generally considered less suitable habitats for pollinators compared with non-urbanized areas due to various factors such as habitat loss, fragmentation, and environmental pollution [10]. Additionally, forest loss and soil sealing associated with urban expansion are major factors that reduce plant resources, leading to a shortage of food resources for pollinators [11]. Despite these vulnerabilities, urban green spaces are increasingly recognized as beneficial for the recovery of pollinator populations [12]. As the importance of biodiversity in urban areas has been recognized,

many cities worldwide have planted numerous trees over the past several decades, increasing plant diversity [13] and, consequently, urban pollinator diversity [14,15]. Undoubtedly, the high pollinator diversity and abundance levels recorded in urban green spaces offer an optimistic outlook for improving pollinator-friendly urban environments [16–20].

Street and ornamental trees are important components of urban green spaces, not only contributing to human well-being and mental health [21] but also serving as vital food sources for pollinators [22–25]. Considering the significant impact that food resources harvested from flowers have on maintaining pollinator populations, providing urban pollinators with high-quality, nutritionally balanced diets is essential for their growth and development [26,27]. Additionally, managing and establishing plants with staggered blooming periods to ensure a continuous supply of food resources is essential [28–30]. Unfortunately, however, the selection of street trees today has primarily been based on human-centered values such as aesthetic appeal, economic cost, air pollution mitigation, pest sensitivity, and maintenance costs [31,32]. The aspect of providing food resources for pollinators in urban areas has not been sufficiently considered [33]. Therefore, to effectively manage floral resources in urban areas or to establish ‘bee pastures,’ more extensive knowledge about the quantity and quality of floral rewards provided by urban trees is required [34].

Furthermore, since the concentration and composition of sugars and amino acids in nectar vary among plant species [35–39], the qualitative and quantitative composition of nectar should be individually assessed for each species. Applying a consistent research protocol is crucial to ensure accuracy in interspecies comparisons. Additionally, information on amino acids in floral nectar is still very limited [40]. To the best of our knowledge, no studies have attempted to comprehensively analyze the total production of sugars and amino acids together.

This study quantitatively assessed the total nectar and amino acid production of eight tree species commonly used as street and ornamental trees, applying a consistent research methodology. Our findings can contribute to distinguishing between urban trees that offer more abundant and diverse food resources for pollinators and those that do not. Additionally, the study highlights the risks of relying solely on fragmented information in interspecies comparisons, offering a more comprehensive methodological approach.

2. Results

2.1. Growth and Flowering

The growth characteristics and blooming periods of the sampled trees were recorded (Table 1). The height and canopy width of each species varied due to the different ages of the trees. The canopy width was used to quantify the blooming quantity per unit area for each sampled tree.

Table 1. Results of the survey on growth and flower characteristics.

Species	Height (m)	Crown width (m)	Flowering period	Flowering day
<i>S. commixta</i>	3.3±0.5	3.1±0.4	Apr 23–May 3	11
<i>W. floribunda</i>	3.0	3 x 11 *	Apr 27–May 11	15
<i>S. japonicus</i>	3.3±0.2	2.6±0.3	May 1–May 15	15
<i>A. turbinata</i>	15.7±0.8	11.4±0.4	May 3–May 15	13
<i>C. kousa</i>	3.9±1.7	2.0±0.3	May 12–Jun 7	27
<i>T. amurensis</i>	4.8±1.4	4.5±1.3	Jun 16–Jun 28	14
<i>K. paniculata</i>	5.6±0.9	7.7±0.2	Jun 24–Jul 9	16
<i>H. miconioides</i>	2.1±0.3	1.2±0.2	Aug 24–Sep 14	22

*Data represent the means ± SD. The *W. floribunda* survey data describes the vine plant covering the roof of an iron frame, with the length and width indicated (Refer to Figure 8).

S. commixta and *W. floribunda* began blooming in late April, with flowering periods of 11 and 15 days, respectively. *S. japonicus* and *A. turbinata* started blooming in early May, each with a flowering period of 13 and 15 days, respectively. *C. kousa* bloomed for approximately a month, from mid-May

to early July. *T. amurensis* and *K. paniculata* began blooming in mid to late June, with flowering periods of 14–16 days. The latest blooming species was *H. miconioides*, which flowered for 22 days from August 24 to September 14.

We surveyed the blooming quantity per tree and multiplied it by the number of trees per hectare, calculated based on canopy width, to estimate the number of flowers per hectare (Table 2). Although *A. turbinata* had the highest number of flowers per tree, *T. amurensis* had the highest number of flowers per hectare. Similarly, while *W. floribunda* had 3.5-fold more flowers per tree than *S. commixta*, their number of flowers per hectare was similar. In contrast, *H. miconioides* had only 1.8-fold more flowers per tree than *C. kousa*, but the difference in the number of flowers per hectare was greater, with *H. miconioides* having 5.3-fold more.

Table 2. Blooming abundance and number of flowers per hectare in eight urban tree species.

Species	Number of flowers per tree (thous.)		Number of flowers per ha (thous.)	
	Mean±SD	Min - Max	Mean±SD	Min-Max
<i>S. commixta</i>	49.5±20.7 ^d	21.6–82.1	51,515±21,540 ^b	22,441–85,401
<i>W. floribunda</i>	174.0±40.9 ^c	134.6–216.2	52,723±12,393 ^b	40,785–65,526
<i>S. japonicus</i>	0.6±0.0 ^e	0.4–0.7	829±154 ^d	633–976
<i>A. turbinata</i>	824.7±104.1 ^a	720.6–928.8	63,460±8,009 ^b	55,450–71,469
<i>C. kousa</i>	2.0±0.7 ^e	1.1–2.6	4,943±1,661 ^a	2,811–6,559
<i>T. amurensis</i>	182.3±50.0 ^c	100.4–279.6	90,019±24,814 ^a	49,556–138,050
<i>K. paniculata</i>	318.3±50.9 ^b	267.4–369.2	53,684±8,589 ^c	45,094–62,273
<i>H. miconioides</i>	3.7±1.3 ^e	2.0–6.2	25,600±9,237 ^c	14,000–42,933
<i>p</i> -value	< 0.0001	-	< 0.0001	-

Data represent the means ± SD. Data were subjected to one-way ANOVA with post-hoc comparisons using Duncan's multiple range test at the 5% significance level. Different letters in each column indicate statistical differences.

2.2. Nectar Volume and Composition

Significant differences in nectar volume per flower were observed among the eight tree species (Figure 1, $p < 0.0001$). *S. japonicus* had the highest nectar volume per flower at $3.71 \pm 1.18 \mu\text{L}$, followed by *H. miconioides* at $2.67 \pm 0.38 \mu\text{L}$, *A. turbinata* at $1.23 \pm 0.10 \mu\text{L}$, *W. floribunda* at $0.90 \pm 0.26 \mu\text{L}$, *T. amurensis* at $0.72 \pm 0.12 \mu\text{L}$, *K. paniculata* at $0.61 \pm 0.18 \mu\text{L}$, *C. kousa* at $0.34 \pm 0.06 \mu\text{L}$, and *S. commixta* at $0.11 \pm 0.03 \mu\text{L}$.

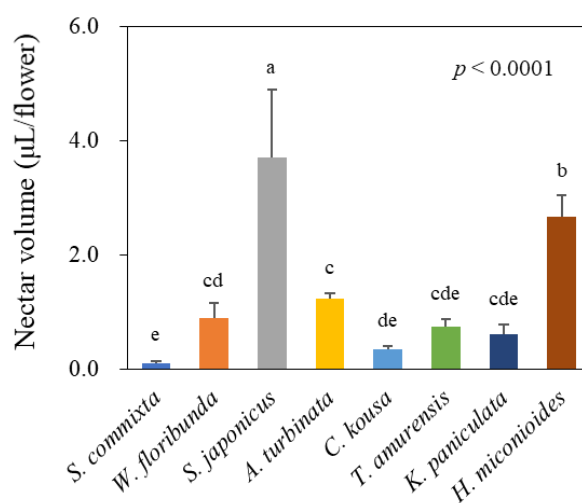


Figure 1. Nectar volume per flower of eight tree species. Data were subjected to one-way ANOVA with post-hoc comparisons using Duncan's multiple range test at the 5% significance level. Different letters above each bar indicate significant differences between the tree species.

2.3. Sugar Content

Significant differences in the sugar content per unit volume were observed among the tree species (Figure 2A, $p < 0.0001$). *T. amurensis* had the highest free sugar content per unit volume at $1,345.8 \pm 313.7 \mu\text{g}/\mu\text{L}$, whereas *C. kousa* had the lowest at $128.2 \pm 26.2 \mu\text{g}/\mu\text{L}$, a more than 10-fold difference. The second-highest free sugar content per unit volume was found in *A. turbinata* ($919.5 \pm 107.8 \mu\text{g}/\mu\text{L}$), followed by *K. paniculata* ($735.3 \pm 183.8 \mu\text{g}/\mu\text{L}$), *W. floribunda* ($723.8 \pm 154.9 \mu\text{g}/\mu\text{L}$), *H. miconioides* ($600.8 \pm 119.9 \mu\text{g}/\mu\text{L}$), *S. japonicus* ($453.6 \pm 64.5 \mu\text{g}/\mu\text{L}$), and *S. commixta* ($254.5 \pm 20.0 \mu\text{g}/\mu\text{L}$).

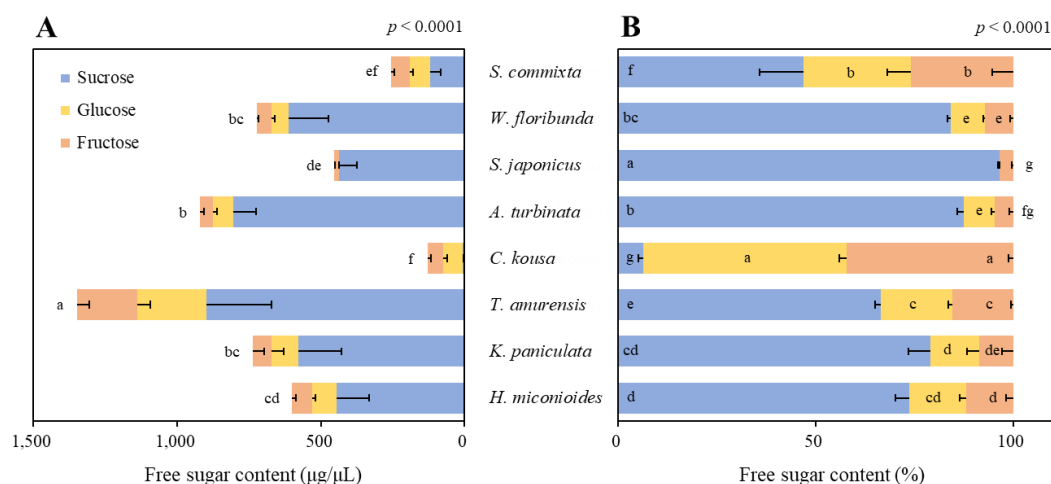


Figure 2. Sugar content (A) and composition (B) of eight urban tree species. Data were subjected to one-way ANOVA with post-hoc comparison using Duncan's multiple range test at the 5% level. Different letters before (A) and within (B) each bar indicate statistical differences.

The sugar composition of the nectar showed that all species except *C. kousa* were dominated by sucrose, with significant differences among species (Figure 2B, $p < 0.0001$). In particular, *S. japonicus* contained 96.5% sucrose with no detectable glucose. *W. floribunda* and *A. turbinata* had sucrose compositions of over 80% (84.3 and 87.5%, respectively), while *K. paniculata* and *H. miconioides* had over 70% sucrose (79.0 and 73.6%, respectively). In contrast, *C. kousa* was dominated by glucose and fructose at 51.4 and 42.2%, respectively, compared with only 6.5% sucrose.

To verify the differences in sugar composition ratios, we analyzed the correlations (Figure 3). The sucrose to hexose ratio (SH ratio) exhibited different patterns among the species, with significant variability (0.1–28.1, $p < 0.0001$). All species except *C. kousa* were classified as sucrose-dominant (sucrose 51–100%), whereas *C. kousa* was classified as hexose-dominant (sucrose 0–9%) (Figure 3A).

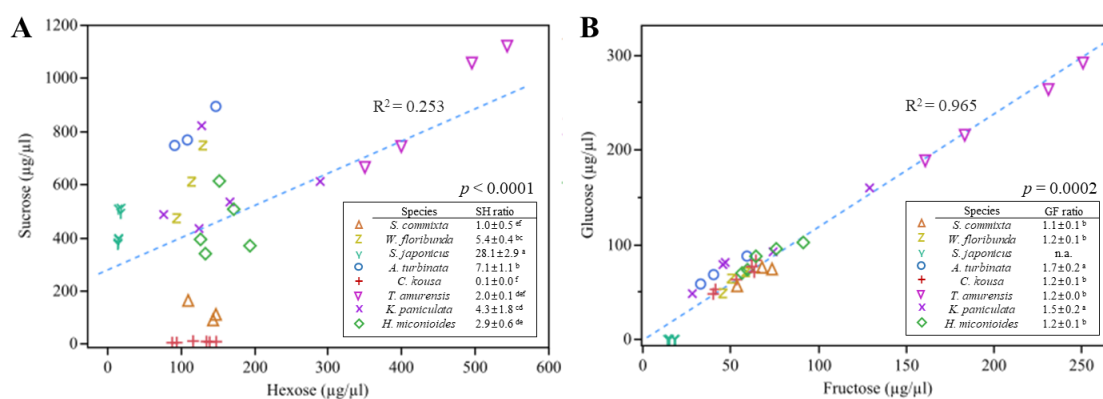


Figure 3. Correlation analysis of sugar content. (A) Sucrose to hexose correlation. (B) Glucose to fructose correlation. Insets in (A) and (B) show sucrose to hexose (SH) and glucose to fructose (GF) ratios, respectively, in the eight street tree species.

A very high positive correlation was found in the ratio of glucose to fructose across all species (Figure 3B, $R^2 = 0.965$), suggesting that when sucrose is hydrolyzed into glucose and fructose, they are produced at nearly equal concentrations, although glucose was slightly more prevalent than fructose (over 1.0). However, variability among the species was observed ($p = 0.0002$).

2.4. Amino Acid Content and Composition

Significant differences in the content of amino acids per unit volume were observed among the tree species (Figure 4A, $p < 0.0001$). *S. japonicus* had a significantly higher amino acid content ($785.2 \pm 11.4 \mu\text{g/L}$) compared with those of the other species, followed by *H. miconioides* with $439.3 \pm 63.7 \mu\text{g/L}$. *W. floribunda*, *C. kousa*, and *K. paniculata* had similar amino acid contents of 363.4 ± 43.1 , 381.9 ± 31.2 , and $351.2 \pm 38.3 \mu\text{g/L}$, respectively, while *S. commixta* ($118.6 \pm 18.6 \mu\text{g/L}$) and *A. turbinata* ($125.0 \pm 11.5 \mu\text{g/L}$) had the lowest amino acid contents per unit volume.

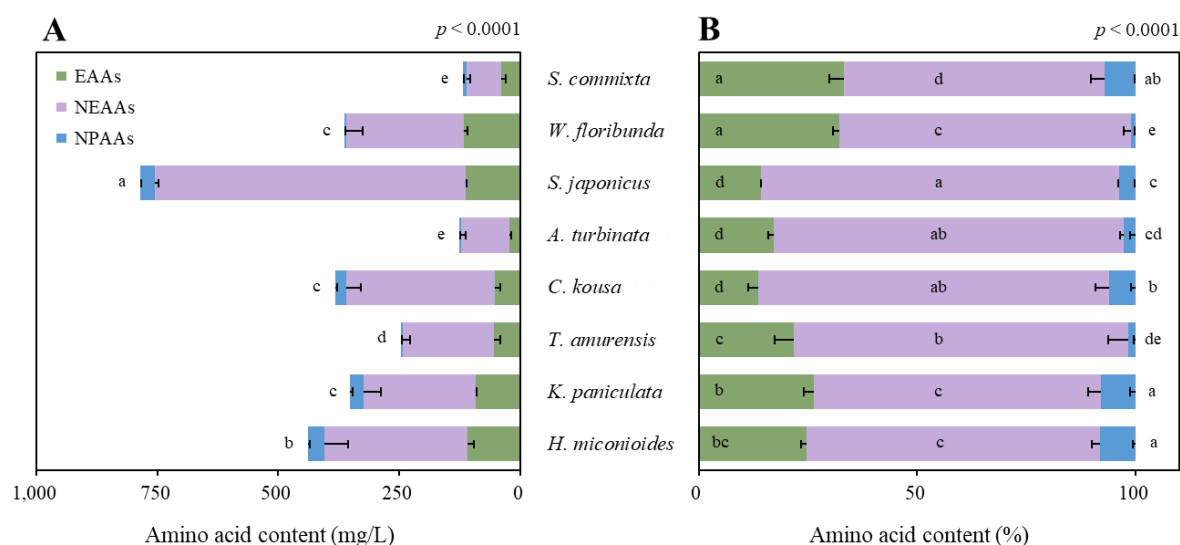


Figure 4. Amino acid content (A) and composition (B) of the eight urban trees in Korea. Data were subjected to one-way ANOVA with post-hoc comparison using Duncan's multiple range test at the 5% level. Different letters before (A) and within (B) each bar indicate statistical differences. Explanations: EAAs, essential amino acids; NEAAs, non-essential amino acids; NPAAAs, non-protein amino acids.

The analysis of the amino acid composition in the floral nectar, categorized into essential, non-essential, and non-protein amino acids, also revealed significant differences among the species (Figure 4B, $p < 0.0001$). Generally, all species had non-essential amino acids (59.7–80.3%) as the largest proportion, followed by essential amino acids (13.6–33.3%) and non-protein amino acids (1.0–8.1%). *S. commixta* and *W. floribunda* had higher proportions of essential amino acids than those of the other species, whereas *K. paniculata* and *H. miconioides* had relatively higher proportions of non-protein amino acids.

The floral nectar of the eight tree species contained 16–22 amino acid types (Figure 5). Among the 10 essential amino acids, arginine, isoleucine, leucine, phenylalanine, threonine, and valine were present in all tree species, whereas methionine was found only in *W. floribunda* and *H. miconioides*. As a result, *W. floribunda* and *H. miconioides* contained all 10 essential amino acids, *A. turbinata*, *T. amurensis*, and *K. paniculata* contained 9, *S. commixta* contained 8, and *S. japonicus* and *C. kousa* contained 7 and 6, respectively. All nine non-essential amino acids were found in all species except for tyrosine, which was absent in *S. commixta*. Among the non-protein amino acids, GABA was found in all species, whereas citrulline was found only in *S. japonicus* and *K. paniculata*, and taurine and ornithine were found only in *K. paniculata*.

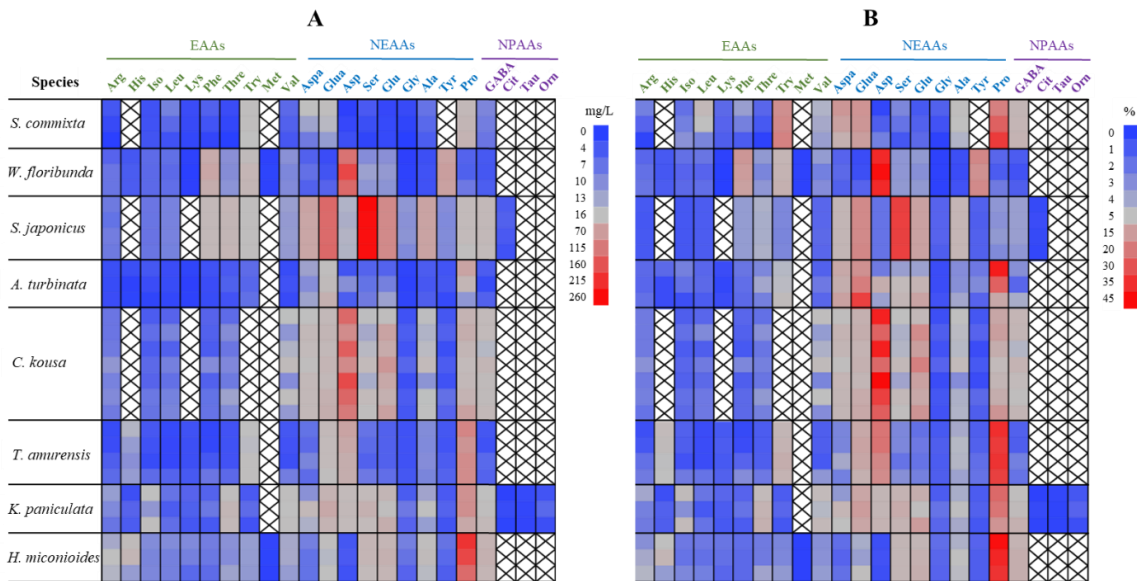


Figure 5. Detailed comparison of amino acid content (A) and composition (B) of eight street tree species in Korea. Explanations: Arg, arginine; His, histidine; Iso, isoleucine; Leu, leucine; Lys, lysine; Phe, phenylalanine; Thre, threonine; Try, tryptophane; Val, valine; Aspa, aspartic acid; Glua, glutamic acid; Asp, asparagine; Ser, serine; Glu, glutamine; Gly, glycine; Ala, alanine; Tyr, tyrosine; Pro, proline; Cit, citrulline; Tau, taurine; Orn, ornithine; NPAAAs, non-protein amino acids.

Among the 15–23 amino acids found in each species, the dominant amino acids (comprising more than 10% of the total) were as follows (Figure 5B, shown in light red to red): proline (26.0%), tryptophan (16.6%), glutamic acid (13.2%), and aspartic acid (10.8%) were predominant in *S. commixta*; asparagine (39.5%), tyrosine (16.2%), and phenylalanine (12.6%) were predominant in *W. floribunda*; serine (32.6%) and glutamic acid (16.8%) were predominant in *S. japonicus*; proline (25.3%) and glutamic acid (22.0%) were predominant in *A. turbinata*; asparagine (32.9%) and glutamine (12.5%) were predominant in *C. kousa*; proline (34.4%) and asparagine (18.7%) were predominant in *T. amurensis*; proline (19.6%) and glutamic acid (10.9%) were predominant in *K. paniculata*; proline (39.0%) was predominant in *H. miconioides*.

2.5. Production Potential of Sugar

The sugar content per flower, calculated by multiplying the nectar volume per flower by the sugar content per unit volume, showed significant variability among tree species (Figure 6A, $p < 0.0001$). *S. japonicus* (1.68 ± 0.24 mg/flower) and *H. miconioides* (1.61 ± 0.32 mg/flower) had relatively high values. They were followed by *A. turbinata* (1.13 ± 0.13 mg/flower), *T. amurensis* (0.97 ± 0.23 mg/flower), *W. floribunda* (0.65 ± 0.14 mg/flower), *K. paniculata* (0.45 ± 0.11 mg/flower), *C. kousa* (0.04 ± 0.01 mg/flower), and *S. commixta* (0.03 ± 0.00 mg/flower).

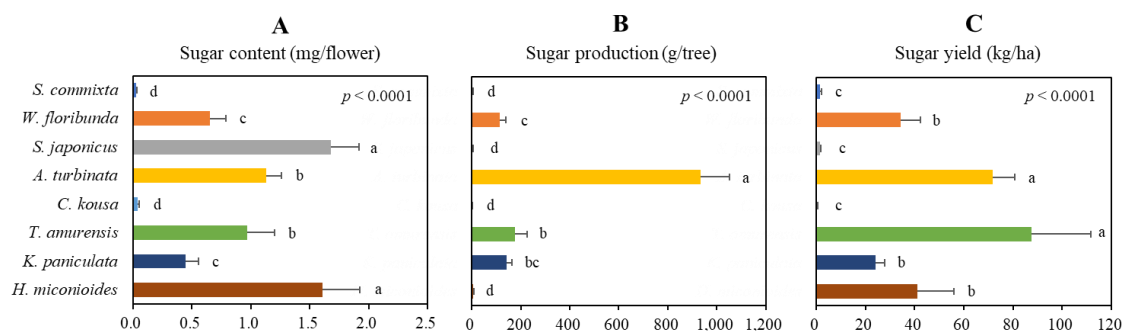


Figure 6. Assessment of sugar content per flower (A), production per tree (B), and yield per hectare (C) among eight urban tree species. Data were subjected to one-way ANOVA with post-hoc

comparison using Duncan's multiple range test at the 5% level. Different letters after each bar indicate significant differences.

The sugar production per tree resulted in a significant change in ranking among the tree species (Figure 6B, $p < 0.0001$). *A. turbinata* showed the highest production (932.7 ± 117.7 g/tree), followed by *T. amurensis* (177.4 ± 48.9 g/tree), *K. paniculata* (142.2 ± 22.8 g/tree), and *W. floribunda* (113.3 ± 26.6 g/tree). *H. miconioides* (5.9 ± 2.1 g/tree), *S. commixta* (1.4 ± 0.6 g/tree), *S. japonicus* (0.9 ± 0.2 g/tree), and *C. kousa* (0.1 ± 0.0 g/tree) showed relatively low production.

The sugar yield per hectare, based on the number of flowers per hectare, was highest in *T. amurensis* (87.6 ± 24.1 kg/ha), with *A. turbinata* (71.8 ± 9.1 kg/ha) also performing well. *H. miconioides* (41.1 ± 14.8 kg/ha), *W. floribunda* (34.3 ± 8.1 kg/ha), and *K. paniculata* (24.0 ± 3.8 kg/ha) showed relatively good nectar production, whereas *S. commixta* (1.4 ± 0.6 kg/ha), *S. japonicus* (1.4 ± 0.3 kg/ha), and *C. kousa* (0.2 ± 0.1 kg/ha) exhibited very low performance (Figure 6C, $p < 0.0001$).

2.6. Production Potential of Amino Acid

S. japonicus had the highest amino acid content per flower at 2.91 ± 0.04 $\mu\text{g}/\text{flower}$, followed by *H. miconioides* at 1.17 ± 0.17 $\mu\text{g}/\text{flower}$. The other six species had amino acid production per flower ranging from 0.13 to 0.33 $\mu\text{g}/\text{flower}$, with *S. commixta* having the lowest production (Figure 7A).

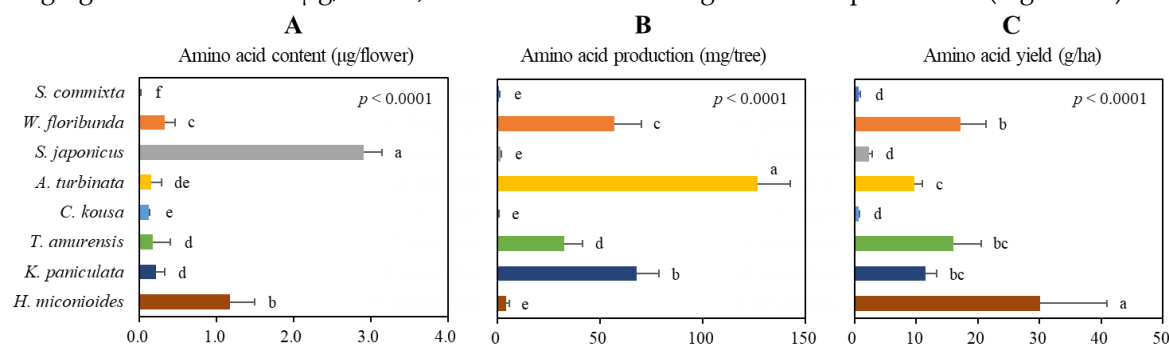


Figure 7. Assessment of amino acid content per flower (A), production per tree (B), and yield per hectare (C) among eight urban tree species. Data represent the mean \pm SD. Data were subjected to one-way ANOVA with post-hoc comparison using Duncan's multiple range test at the 5% level. Different letters after each bar indicate significant differences.

Based on the number of flowers per tree, *A. turbinata* had the highest amino acid production per tree at 126.8 ± 16.0 mg/tree, followed by *K. paniculata* (67.9 ± 10.9 mg/tree), *W. floribunda* (56.9 ± 13.4 mg/tree), and *T. amurensis* (32.5 ± 9.0 mg/tree), all showing significant production levels. In contrast, the other four species (*S. commixta*, *S. japonicus*, *C. kousa*, and *H. miconioides*) had very low productivity, ranging from 0.6 to 4.3 mg/tree (Figure 7B).

In terms of amino acid yield per hectare, *H. miconioides* had the highest at 30.1 g/ha, followed by *W. floribunda* (17.2 ± 4.1 g/ha), *T. amurensis* (16.1 ± 4.4 g/ha), *K. paniculata* (11.5 ± 1.8 g/ha), and *A. turbinata* (9.8 ± 1.2 g/ha). The other three species (*S. commixta*, *S. japonicus*, and *C. kousa*) had very low yields, ranging from 0.6 to 2.4 g/ha (Figure 7C).

3. Discussion

3.1. Evaluating the Usefulness of Floral Resources Requires a Comprehensive Consideration of Various Factors

Our study emphasizes that evaluating the usefulness of urban floral resources for pollinators requires a comprehensive consideration of various factors. We identified significant variability in the potential total sugar and amino acid production among the tree species. Notably, when the results of nectar volume per flower, sugar and amino acid content per unit volume, and the number of flowers for comparison between species were standardized using production potential per tree and per

hectare, the rankings of the species changed significantly. For example, *T. amurensis* ranked only fifth in nectar secretion per flower (Figure 2), but due to its high sugar content per unit volume (Figure 3A) and large number of flowers (Table 2), it rose to first place in sugar yield per hectare (Figure 7). Conversely, *S. japonicus* exhibited excellent production per flower due to its high nectar volume per flower, but its very low number of flowers per tree and per hectare resulted in it ranking the lowest in total sugar and amino acid production potential (Figures 7 and 8).



Figure 8. Flower morphology and nectar foraging by honeybees in eight urban tree species.

On the other hand, *H. miconioides*, which ranked second in sugar and amino acid content per flower, had low production per tree due to a small number of flowers. However, this was because the surveyed trees had a small canopy width of 1.2 m (fewer flowers per tree but more trees per hectare). As a result, *H. miconioides* ranked third in sugar productivity and first in amino acid production per hectare, making it an excellent food tree for pollinator. Another example is *A. turbinata*, which had relatively low nectar volume and amino acid content per flower, resulting in very low amino acid production per flower. However, due to the large number of flowers per tree, it ranked first in amino acid production per tree. Nevertheless, this was an illusion caused by surveying large trees with many flowers per tree, and its actual amino acid production per hectare ranked only fifth overall.

Potential total sugar and amino acid production is recognized as a good indicator for evaluating the availability of floral resources [19]. However, due to differences not only among species [22,23,41–43] but also within varieties of the same species [24,44,45]), individual studies are required for each plant species, applying the same measurement criteria. Particularly, evaluating tree species is challenging because it is almost impossible to use materials of the same age or size. Therefore, our case study can serve as a valuable reference. Our study further clarifies the inadequacy of using fragmented information alone to evaluate the value of floral resources in terms of providing food resources for pollinators. Concluding that floral resources are either highly valuable or lacking based solely on fragmented information about the plant may be premature.

3.2. Sugar and Amino Acid Availability

Considering the dependency of pollinators on floral resources [12,46], flowers that are attractive to pollinators must provide sufficient profitable rewards such as sugars, proteins, and amino acids [47]. Therefore, to achieve the fundamental goal of improving pollinator-friendly habitats, expanding our knowledge of the floral resources provided by different tree species is essential [25]. Accordingly, we quantified and compared the sugar and amino acid production of the eight urban tree species in Korea (Figures 7 and 8). The results showed that sugar productivity was highest in *T. amurensis* (87.6 kg/ha), followed by *A. turbinata* (71.8 kg/ha), *H. miconioides* (41.1 kg/ha), and *W. floribunda* (34.3 kg/ha). Amino acid productivity ranked as follows: *H. miconioides* (30.1 g/ha) > *W. floribunda* (17.2 g/ha) > *T. amurensis* (16.6 g/ha) > *K. paniculata* (11.5 g/ha). Notably, the sugar and amino acid productivity rankings were not consistent (Figure 8). For example, *T. amurensis*, which had the highest sugar production, ranked third in amino acid production, while *S. japonica*, which ranked third in sugar

production, ranked first in amino acid production. Meanwhile, *A. turbinata*, which had the second-highest sugar production, only ranked fifth in amino acid productivity. *S. commixta*, *S. japonicus*, and *C. kousa* were found to produce very low amounts of sugars and amino acids. Therefore, we do not recommend these three species for enhancing energy sources for insect visitors in urban areas.

The qualitative and quantitative composition of amino acids varies among and within species [38,39]. The functional significance of amino acids to pollinators is still under discussion [40], but they clearly offer more than just nutritional rewards [48]. Honeybees that consume various amino acids exhibit increased lifespan and fecundity as well as improved memory and learning abilities [49,50]. Our study not only highlights the significant differences in amino acid productivity among the eight species but also emphasizes the compositional differences between them. The variation in amino acid composition among species that bloom at different times can potentially provide pollinators with more nutritionally balanced food resources. For instance, in our study, the nectar of *S. commixta* lacked histidine, methionine, and tyrosine, which were available from *W. floribunda*, which blooms at a similar time. Similarly, *S. japonicus* nectar lacked histidine, lysine, and methionine, but these were present in the nectar of *A. turbinata*, which blooms almost simultaneously. Conversely, *S. japonicus* had elevated levels of phenylalanine, threonine, tryptophan, aspartic acid, glutamic acid, serine, and glutamine, which were relatively low in *A. turbinata* (Figure 5A). Considering the complementary relationship between *T. amurensis* and *K. paniculata*, which bloom sequentially, *T. amurensis* had higher levels of histidine, tryptophan, and asparagine, whereas *K. paniculata* had higher levels of isoleucine, threonine, aspartic acid, and serine.

Recent studies have highlighted the importance of non-protein amino acids (NPAAs) in nectar. While the functional significance, biological roles, and association with different types of pollinators are still not fully understood [40,51,52], Carlesso et al. [53] suggested that NPAAs in nectar might be a cooperative strategy that enhances the transfer of pollen between conspecific plants by encouraging pollinators to learn and recognize the traits of the associated flowers. Additionally, Nepi [48] noted that NPAAs in nectar could potentially influence nectar-mediated plant-animal interactions and play a role in protecting nectar from microbial invasion. Our study found that the concentrations of NPAAs in the nectar of the eight tree species ranged from 1.0 to 8.1%, with significant variability (Figure 5B). GABA was consistently detected as the most abundant NPAA (Figure 6). GABA is a prominent NPAA in floral nectar [54,55] and is the most abundant inhibitory neurotransmitter in the insect brain [56]. This amino acid plays essential roles in olfactory processing and learning [57,58] and is known to enhance the memory capabilities of honeybees [53]. Additionally, in our study, taurine, which was found only in *K. paniculata*, is an important neuromodulator in the insect brain along with GABA and β -alanine and can interact with the neural activity of nectar foragers shortly after ingestion [59,60].

3.3. Limitations

Our study has several limitations. First, our findings are based on observations over a single year. Blooming periods and flower abundance have been established to vary significantly from year to year [24,42]. Additionally, various factors can influence volume and concentration of nectar (reviewed in [61]). Therefore, continuous monitoring and repeated studies are necessary. Second, we did not assess pollen production and quality. Pollen is also a crucial food resource for pollinators, and differences in pollen production among plant species have been confirmed in several previous studies [41,62]. The three species that recorded low sugar and amino acid rewards in our study (*S. commixta*, *S. japonicus*, and *A. turbinata*) may have significant pollen reward values. We clearly recognize the limitations of this study and plan future research to address these issues.

4. Material and Methods

4.1. Study Site and Tree Species

The study species comprised eight tree species commonly planted in parks and as street trees and ornamental trees in the urban areas of South Korea (Figure 8). *Sorbus commixta* Hedl., *Styrax*

japonicus Siebold & Zucc., *Aesculus turbinata* Blume, *Tilia amurensis* Rupr., *Koelreuteria paniculata* Laxm. are designated as honey plants under the 'Beekeeping Industry Promotion and Support Act' and are recommended for the establishment of honey plant complexes in South Korea. *Wisteria floribunda* (Willd.) DC and *Cornus kousa* Bürger ex. Hance are well-known to Korean beekeepers as excellent honey plants, while *Heptacodium miconioides* is a honey plant newly discovered by our research team.

The trees under investigation were planted for landscape purposes at the Division of Forest Biological Resources, National Institute of Forest Science, Suwon, South Korea (37° 15' 55" N and 126° 57' 29.9" E, elevation: 44 m). They were growing healthily without pest damage and competition from surrounding trees. Three to seven trees per species were used in the experiment.

We recorded the start and duration of blooming in 2022. Blooming was considered to have started when more than 5% of the total flower buds had bloomed. Full bloom was recorded when the cumulative blooming rate reached 45–55%, and termination of blooming was recorded when more than 95% of the flowers had bloomed and withered. The abundance of flowering was surveyed between the start of blooming and full bloom. The number of flowers per tree was calculated as the product of the number of inflorescences per tree and the number of flowers per inflorescence [23]. The number of flowers per inflorescence included both bloomed and unbloomed flowers. The number of flowers per hectare was calculated by multiplying the number of flowers per tree by the number of trees per hectare, which was determined by dividing 10,000 m² (1 ha) by the square of the tree's canopy width.

4.2. Nectar Measurement

Nectar volume measurements were conducted at the full bloom phase for each tree. All previously bloomed flowers were removed (at 4:00 p.m.), and pollination bags with a pore size of 0.3 mm were used to prevent nectar loss. Since the lifespan of the flowers of all tree species was 2 days, we collected at least 100 flowers on the second day after bagging them. Afterward, we carefully removed unnecessary parts (such as petals and peduncles) to the extent that nectar loss was minimized and placed the flowers in a 50-mL tube equipped with nylon mesh. These tubes were centrifuged at 4,000 rpm for 4 min. The collected nectar in the tubes was quantified using 50–100 µL syringes. After adding 10 volumes of 80% ethanol (v/v), the nectar was further purified using a 0.45-µm centrifugal filter to remove pollen included in the nectar. The samples were stored frozen at -20°C until the analysis of sugars and amino acid content.

4.3. Sugar and Amino Acid Analysis

The analysis of free sugar content was performed using an HPLC system (Dionex Ultimate 3000; Dionex, Sunnyvale, CA, USA). The mobile phase was deionized water at a flow rate of 0.5 mL/min, and the column oven was maintained at 80°C. Detection was achieved using a Shodex Ri-101 (Showa Denko America, Inc., New York, NY, USA) coupled with an Aminex 87P column (300 × 7.8 mm, Bio-Rad Laboratories, Hercules, CA, USA). Free sugars were quantified using the external standard method; high-purity standards (99.5%) of sucrose, glucose, and fructose (Sigma-Aldrich, St. Louis, MO, USA) were used.

4.4. Amino Acid Content and Composition

The collected nectar samples were analyzed for amino acids using *O*-phthalaldehyde (OPA) and fluorenylmethyl chloroformate (FMOC) derivatization. The samples were sequentially mixed with borate buffer, OPA/mercaptopropionic acid, and FMOC reagent and then analyzed using an HPLC 1200 series system (Agilent Technologies, Santa Clara, CA, USA). The mobile phase consisted of two solutions: Solution A, containing 10 mM Na₂HPO₄ and 10 mM Na₂B₄O₇·10H₂O at pH 8.2, and Solution B, a mixture of water, acetonitrile, and methanol in a 10:45:45 ratio. The gradient conditions were set to start at 100:0 (v/v, %) of Solution A to Solution B from 26 to 28 min, changing to 0:100 from 28 to 30.5 min, and then reverting to 100:0 after 30.5 min. The flow rate was maintained at 1.5 mL/min with an injection volume of 0.5 µL. The INNO C-18 column (150 mm × 4.6 mm, 5 µm; Youngjin Biochrom

Co., Ltd., Seongnam, Republic of Korea) was maintained at 40°C. The UV detector was set at 338 nm, and for fluorescence detection, the OPA derivative was monitored at emission and excitation wavelengths of 450 and 340 nm, respectively, while the FMOC derivative was detected at emission and excitation wavelengths of 305 and 266 nm, respectively.

4.5. Production Potential

We estimated the potential production using the nectar secretion volume, sugar and amino acid content per unit volume, and the number of flowers per tree and per hectare. The sugar and amino acid production per flower were calculated by multiplying the nectar volume per flower by the respective content per unit volume. Finally, the nectar and amino acid yield per hectare were determined using the number of flowers per hectare.

$$\text{Honey yield (kg/ha)} = \text{Nectar contents (mg/flower)}^a \times \text{Number of flower (ea/ha)} \times 0.000001 \text{ (for unit conversion: mg to kg)}$$

^a Nectar content (mg/flower) = Nectar volume ($\mu\text{L}/\text{flower}$) \times Free sugar content ($\mu\text{g}/\mu\text{L}$) \times 0.001 (for unit conversion: μg to mg).

4.6. Statistics

The collected data were analyzed using the integrated statistical software package SAS 8.2 (SAS Institute, Cary, NC, USA) to identify differences in the number of flowers, nectar secretion volume, free sugar and amino acid content per unit volume, and nectar and amino acid production among the species through one-way analysis of variance (ANOVA). Post-hoc comparisons were performed using Duncan's multiple range test (significance level < 0.05).

5. Conclusions

We quantitatively evaluated the floral resource availability (total sugar and amino acid production) of eight tree species recommended for planting in urban green spaces in South Korea. Although these eight species are known as excellent nectar plants in Korea, information provided by non-experts should be considered with caution. We found that sugar availability varied by up to 438-fold and amino acid production by up to 50-fold between species. Moreover, tree species with high total sugar production did not always align with those with high amino acid production. Therefore, selecting pollinator-friendly plant species should be based on a comprehensive survey and analysis of various factors, such as nectar volume, concentration per unit volume, and standardized flower numbers per tree and per hectare. Lastly, we propose the continuous accumulation of data, such as that presented in Figure 9, which shows the blooming periods, sugar, and amino acid productivity, to improve and manage sustainable habitats and food resources for pollinators in urban environments.

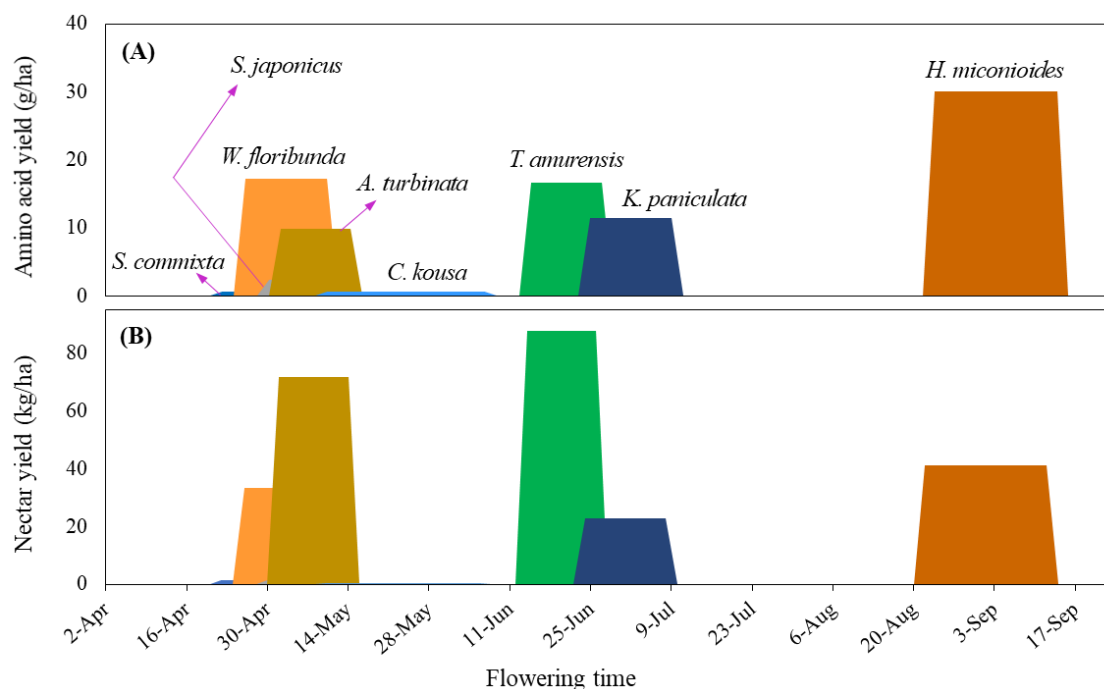


Figure 9. Comparison of amino acid (A) and nectar (B) productivity by flowering time. By continuously accumulating such data, we can identify urban pollinators with nutritionally balanced and continuous food resources year-round.

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