



Water-Saving Green Roofs for Pollinators

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Abstract

Appropriately designed green roofs can function as water-saving irrigation systems and pollinator habitats. In this study, we evaluated a rooftop irrigation system using reclaimed water (simulated by diluted seawater up to 18 dS m⁻¹) to sustain vegetation (turf grass *Cynodon dactylon* and the Crassulacean acid metabolism [CAM] species *Sedum kamtschaticum* and *S. oryzifolium*) under drought and salinity stress. A stress factor, the time integral of the soil water potential that exceeds a threshold for normal growth, was used to quantify the accumulated plant stress. Moderate stress reduced total evapotranspiration but increased water use efficiency in CAM plants, indicating trade-offs between irrigation frequency and plant water use. Saline irrigation led to cation accumulation in leaves (Na⁺, Ca²⁺, Mg²⁺, and K⁺). Additionally, leaf extract electrical conductivity [ECleaf] was more reliable for assessing plant salt stress than drainage water electrical conductivity. However, ECleaf is not an absolute stress detector. Rather, it is a relative indicator that requires species-specific calibration. These findings support an integrated design framework that balances substrate properties, plant selection, climate conditions, and irrigation scheduling. Key recommendations include prioritizing drought- and salt-tolerant species (especially CAM plants) to reduce water demand, optimizing irrigation intervals to mitigate stress, and adopting renewable energy for automated irrigation. Integrating pollinator-friendly planting with efficient reclaimed water reuse can enhance the sustainability and resilience of green roof ecosystems. However, pollinator-habitat benefits remain theoretical. This demonstrates the need for direct field validation of flowering and visitation responses.

Keywords : green roof; pollinator habitat; reclaimed water reuse; saline irrigation; drought stress; Crassulacean acid metabolism; water-use efficiency

Introduction

Urban rooftop agriculture and green roofs provide greenery, thermal regulation, and habitats for pollinators and biodiversity [1]. For instance, bees pollinate flowering plants and sustain urban ecosystems [2]. Plant diversity and floral abundance strongly influence their diversity and syrphid fly visitation [3]. Urban microclimates, often warmer, benefit thermophilic bees [4]. This

suggests that tropical rooftops can serve as alternative habitats in the presence of vegetation and features such as beehives. Rooftop beekeeping also produces honey for educational purposes and sale [5,6]. However, maintaining bee-friendly vegetation increases irrigation demand, a challenge in water-scarce cities.

In tropical monsoon climates such as Thailand, green roofs face long dry seasons followed by intense rains. Prolonged drought

necessitates non-potable irrigation, whereas heavy rainfall flushes accumulated salts from substrates. This strong seasonality and limited maintenance capacity complicate the provision of year-round pollinator support.

Reclaimed water, particularly secondarily treated domestic graywater from sinks, baths, and laundry, is a practical non-potable source for green roof irrigation. Salinity in irrigation water indirectly affects pollinator support. Specifically, elevated salt concentrations stress vegetation, consequently reducing growth and flowering intensity. This limits the availability of floral resources for pollinators [7]. In addition, raindrop splash erosion and wind-driven particle transport can cause the loss of thin green roof substrates, especially when vegetative cover is incomplete [8]. Substrate loss reduces rooting depth and can clog drainage outlets. These issues become particularly relevant when intense early-monsoon rains fall on partially exposed substrates after the dry season.

Rising urban populations further strain water supplies, resulting in the use of non-potable irrigation (**Figure 1**). Graywater (the primary reclaimed water source considered in this study) and harvested rainwater can significantly reduce potable water-use [9]. In one reuse system

(**Figure 1**), reclaimed water undergoes aerobic and anaerobic treatment [10]. It is stored in a primary tank and subsequently pumped (via renewable energy) to rooftop tanks for irrigation.

The application of such systems in multistory buildings is feasible, as they support well-managed vegetation [11]. However, salinity remains a challenge: even treated water contains residual salts, especially sodium. These salts are costly to remove and accumulate in shallow substrates, thereby stressing plants [12].

Green roof plants must withstand drought and salinity, especially in regions with prolonged dry seasons or competing water demands that restrict the use of freshwater irrigation. Although saline irrigation methods exist for field crops [13, 14], green roof conditions—thin substrates and shallow root zones—are more challenging.

Stress elimination would require intensive management and constant monitoring (**Figure 2**), which is unrealistic for most owners. A more practical strategy is to allow controlled stress to reduce water and labor needs. However, data on the stress tolerance of green roof species are limited, partly because of difficulties in the quantification of cumulative stress.

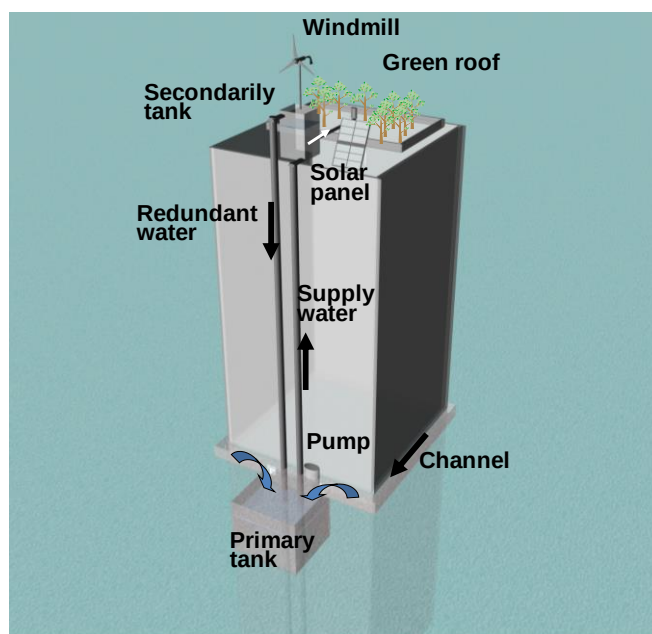


Figure 1 Schematic of reclaimed water collection, treatment/storage, and rooftop reuse for irrigation

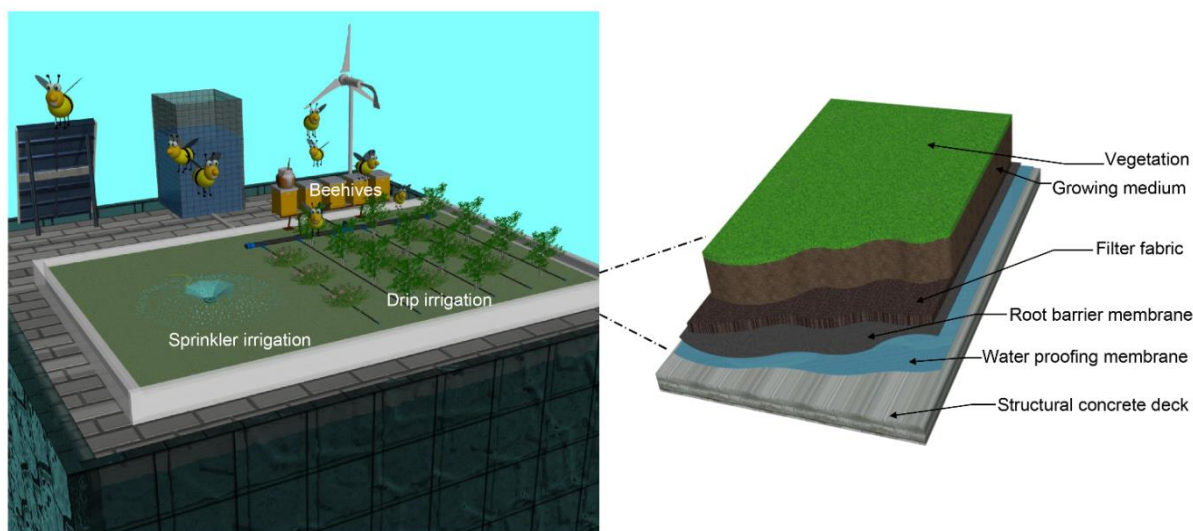


Figure 2 Schematic layout of gray water irrigation for vegetation with beehives (Left) and thin substrate layers of a representative green roof system (Right)

In this study, we aimed to quantify plant stress on a green roof based on the “stress factor” concept. We further sought to evaluate its effects on water use and growth [15]. Finally, we propose strategies for integrating pollinator-friendly habitats with water-saving irrigation, enabling water conservation in rooftops while supporting flowering plants for pollinators.

Materials and Methods

Experimental Conditions

A controlled irrigation experiment was conducted in a glasshouse during the hot summer to simulate the tropical rooftop conditions typical of Thailand’s monsoon cities and pollinator-oriented green roofs. The average temperature and relative humidity were 32 °C and 66%, respectively. Plastic pots (200-cm² surface area) served as micro-green roofs. Each pot contained a 20 cm layer of engineered green roof substrate over 10 cm of coarse perlite gravel for drainage purposes. The gravel acted as a filter, and the bottom of the pot functioned as a root barrier, with drainage outlets collecting excess water (Figure 1). Pots were placed on a sand bed where the surface sand temperature exceeded 50 °C to simulate rooftop heating, and a thin insulating cushion moderated heat transfer to

reproduce dry-season heat loads relevant to bloom suppression and substrate desiccation.

Although the present pot-scale experiment focused on water-use dynamics and salt accumulation, substrate integrity under rainfall is a parallel concern for operational green roofs. Figure 3 shows photographs of related experiments conducted in the same glasshouse facility using the same plant species and engineered substrate as those in this study. The glasshouse slope installation (Figure 3a) accommodated *S. kantschaticum* on six substrate types—including the engineered green roof medium used in this study—at two inclinations (20° and 30°); it was further equipped with overhead nozzles capable of simulating rainfall. A separate rainfall simulation experiment (Figure 3b–e) quantified splash erosion from the same substrate under 40 mm h⁻¹ artificial rainfall delivered from a height of 12 m for approximately 1 h. Bare substrate (Figure 3c) showed substantial splash-driven soil loss; detached particles were deposited on the inner walls of the surrounding collection tray. Partial vegetative cover by turfgrass (Left) and *S. oryzifolium* (Right) (Figure 3d) reduced but did not eliminate splash loss. In contrast, complete canopy closure (≥100% cover) by *S. oryzifolium* (Left) or a nonwoven-sheet ground cover with *S. oryzifolium* (Right) (Figure 3e) virtually eliminated visible splash

erosion. These observations confirm that vegetative cover plays a decisive role in protecting thin green roof substrates from raindrop-impact erosion, a factor with direct implications for the irrigation management strategies discussed below.

Irrigation regime

Diluted seawater with electrical conductivity (EC) levels ranging from 0.7 dS m^{-1} (freshwater) to 18 dS m^{-1} (high salinity) was used as a salinity proxy for reclaimed water. This range was selected to establish dose–response relationships; the lower range ($0.7\text{--}2.0 \text{ dS m}^{-1}$) is representative of treated domestic graywater, whereas the upper range represents worst-case scenarios. Two irrigation regimes were applied: frequent (every 1–3 days) and intermittent (5–17 days) [16]. We imposed a zero-rain condition to simulate a

worst-case Thai dry-season window; multi-week rain-free periods (approximately 41 consecutive days across all experimental periods) occur in inland regions. Accordingly, we did not simulate rainfall (freshwater) events. Such rains would episodically leach salts in real roofs and temporarily raise soil water potential (**Figure 4c**).

Evapotranspiration (ET) was monitored by weighing the pots before irrigation. The irrigation volume equaled $1.2 \times \text{ET loss}$ to permit partial salt leaching, creating a 20% drainage surplus [17]. The drainage volume and EC were recorded to estimate the salt balance. Soil moisture was inferred from the pot weight, and root-zone salinity was assessed using a mass balance of salt inputs (irrigation) and outputs (drainage), adjusted for soil water content. Small evaporation pans near the pots provided reference evaporation data.

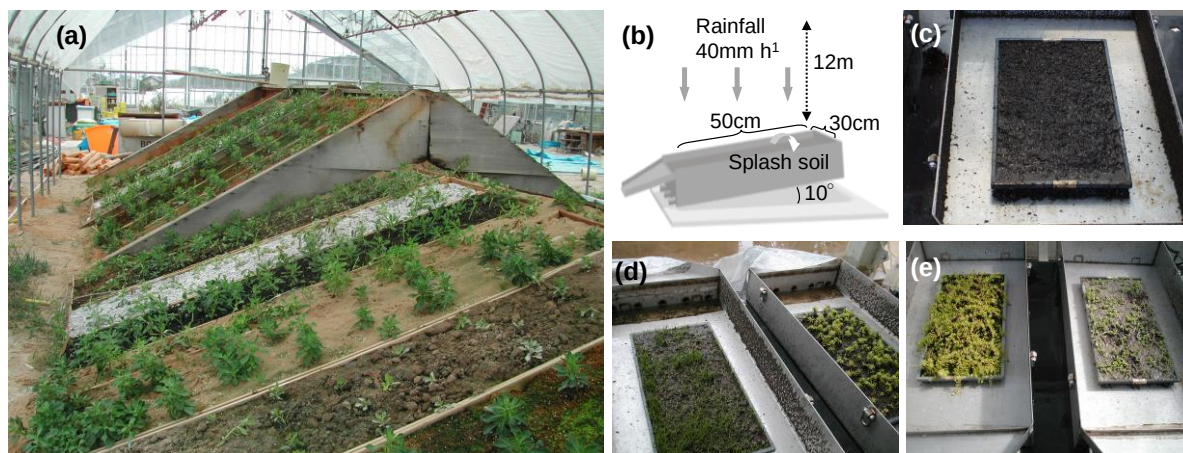


Figure 3 Photographs of related experiments conducted in the same glasshouse facility.

(a) Slope experiment: *S. kamtschaticum* cultivated on six different substrates at two contrasting inclinations; overhead nozzles allow rainfall simulation.

(b) Schematic and overview of the rainfall simulation setup: artificial rain was delivered onto substrate trays from a height of 12 m at 40 mm h^{-1} for approximately 1 h.

(c) Bare substrate after rainfall simulation, showing substantial splash-driven soil loss deposited on the inner walls of the surrounding collection tray.

(d) Partial vegetative cover: turfgrass (left) and *S. oryzifolium* (right) with incomplete canopy closure; splash erosion was reduced compared with bare substrate but remained visible.

(e) Complete vegetative cover ($\geq 100\%$): *S. oryzifolium* (left) and nonwoven-sheet ground cover with *S. oryzifolium* (right); virtually no splash erosion was observed.

All experiments used the same engineered green roof substrate as that in the present study.

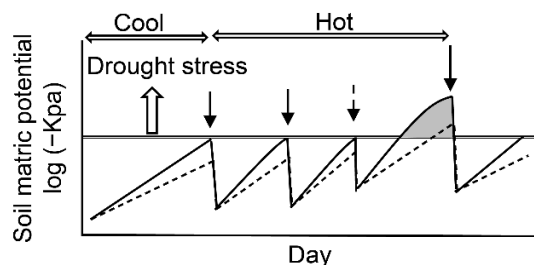
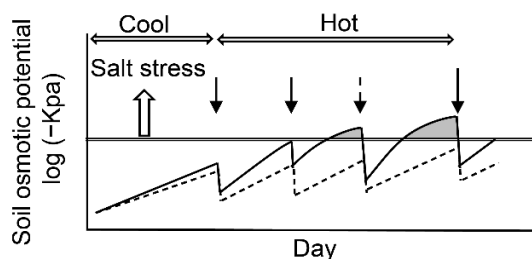
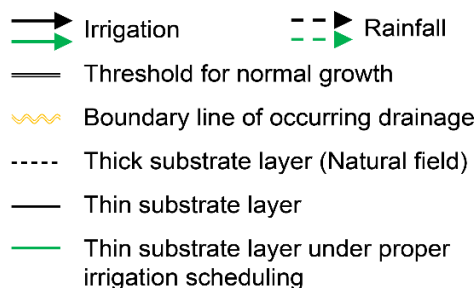
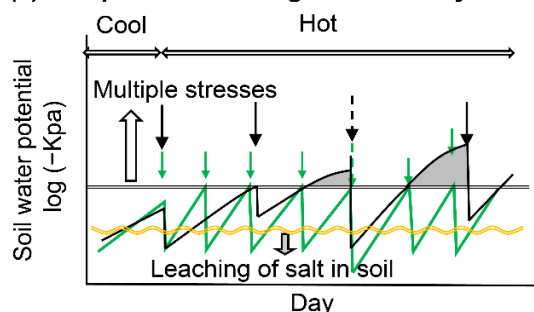
(a) Soil droughtness**(b) Soil salinity****(c) Complex of the drought and salinity in soil**

Figure 4 Illustration of the drought/salinity stress factor, defined as the time-integrated exceedance of soil water potentials beyond growth thresholds

Plant stress assessment

Plant stress was assessed using a stress factor (S) method (**Figure 4**). Soil water potential has two components: matric (related to moisture/drought) and osmotic (related to salinity) potential. Matric potential was derived from soil moisture using a predetermined soil water retention curve, and the osmotic potential was estimated via a linear conversion from EC. The threshold for plant stress was selected as pF 3.0 (approximately -1 kPa), a widely accepted threshold demarcating the limit of readily available water [14, 18]. If the soil matric potential was wetter than the threshold for plant stress, we considered drought stress to be zero; if drier, the excess (in time and magnitude) contributed toward drought stress (Figure 4a). Similarly, salinity stress accumulated when soil salinity (EC) exceeded the plant tolerance threshold (Figure 4b). The total stress factor S was then calculated by integrating the portions of the matric and osmotic potentials that exceeded their respective thresholds (Figure 4c). In

simpler terms, S (MPa-day) represents the cumulative “amount” of water stress (drought plus salinity) experienced by the plant during the experiment [14]. The selected thresholds represent general agronomic benchmarks rather than species-specific calibrations. Thus, S may not perfectly capture differential stress sensitivity across species.

Plant selection and measurements

For sustainable green roofs that use reclaimed water, selecting plants with high drought and salt tolerance while retaining nectar/pollen potential for pollinators, is essential. We focused on three species in this study: one turfgrass species and two succulents.

In tropical regions, *Cynodon dactylon*, *S. kamtschaticum*, and *S. oryzifolium* typically flower between June and September, June and August, and May and July, respectively. Flowering was not observed during our short experimental period; actual phenology under saline irrigation on green roofs may differ from these reference ranges.

C. dactylon (Bermuda grass) is commonly used on roofs because of its resilience; it tolerates moderate salinity and drought and grows naturally in salt-affected habitats (up to 19.9 dS m⁻¹) [19]. In contrast, turfgrass tolerates stress less effectively than Crassulacean acid metabolism (CAM) succulents under extreme conditions [20]. The succulent species *Sedum kamtschaticum* and *S. oryzifolium* use CAM, an adaptation that facilitates water conservation. CAM plants open their stomata at night (when evaporation demand is low) to fix CO₂ into organic acids. They close their stomata during the day while completing photosynthesis internally [21, 22]. This metabolism and water storage significantly reduce transpiration losses in fleshy leaves. These traits enable CAM plants to thrive in thin, dry substrates with minimal irrigation. For example, *Sedum* species can maintain metabolic activity during drought by shifting to CAM and avoiding excessive salt uptake [23]. Owing to these advantages, CAM succulents are ideal for water-limited roofs. However, an all-succulent roof may not provide the best forage for bees. Thus, including some stress-tolerant flowering herbs or grasses can improve the habitat value. *C. dactylon* can bloom and provide pollen, though not as much as wildflowers. This mix reflects Thai monsoon reality: resilient species carry the dry season, whereas flowering herbs enhance rainy-season forage. In addition to their role in habitat provision, dense canopies formed by these species also protect thin substrates from splash erosion (**Figure 3c–e**).

Before starting the irrigation treatments, healthy specimens of each species were cultivated and transplanted into the experimental pots to ensure that the planting density was sufficient to cover the soil surface before the experiment began. The plants were established using non-saline water before initiating the abovementioned irrigation regimes.

Monitoring plant responses

Plant growth and stress indicators were evaluated at the end of the experiment. Above-ground biomass was harvested and oven-dried at 80 °C for 72 h to determine the dry matter

yield (DM). Plant tissue salt accumulation was analyzed by grinding dried shoot material to powder using a mixer mill [24]. A known powder mass was mixed with deionized water and shaken for >24 h to extract soluble salts. The EC of the filtered supernatant was measured to determine the leaf water EC (EC_{leaf}), which reflects the tissue's salt concentration. To account for differences in plant water content, we expressed EC_{leaf} based on the water content using an inversely proportional adjustment. We further measured the concentrations of key cations (Na⁺, K⁺, Ca²⁺, and Mg²⁺) in the leaf extract using the same atomic absorption spectroscopy procedures [24]. Because flowering was not observed during the short trial, canopy biomass served as a proxy for habitat capacity under dry versus rainy analogs.

Results and Discussions

Stress factor

The treatments successfully generated various stress conditions, as reflected in the calculated stress factor (S) values (**Figure 5**). *C. dactylon* experienced the largest S range under intermittent (extensive) irrigation with high salinity, reaching a maximum of 126 MPa·day under water stress alone. In contrast, the two CAM succulents showed considerably lower S values, with a maximum of 34 MPa·day. No significant difference in S was observed between frequent vs. intermittent irrigation at equal salinity. This indicates that CAM plants avoided most of the drought stress by closing their stomata early and markedly reducing water use under dry or saline conditions. The grass, with C3 metabolism, continued to transpire until the soil water was largely depleted, resulting in higher water stress during dry intervals. Frequent saline irrigation alleviated some stress in *C. dactylon*; its S value under frequent 18 dS m⁻¹ irrigation was approximately 67% lower than that under intermittent 18 dS m⁻¹. From a practical standpoint, short-term intensive watering can buffer the dry season to preserve the canopy and prospective bloom sites. Salinity stress accumulated gradually and was partly offset by reduced water demand under stress. However,

this buildup can erode mid-dry-season habitat quality (cover and floral potential) in the absence of seasonal rain.

Water use efficiency (WUE)

Total water use (cumulative ET) was inversely correlated with stress factors (**Figure 5**). Well-watered *C. dactylon* had the highest total evapotranspiration (TET) (574 mm), which sharply declined to 172 mm as S increased. CAM species had inherently lower water use and weaker correlations with S. Furthermore, they reduced water use under stress via stomatal closure and CAM-idling, whereas *C. dactylon* continued to use water at a moderate rate until stress became markedly high. This reflects a fundamental trade-off: CAM plants conserve water at the expense of growth, whereas grass maintains function for longer but risks dehydration.

WUE refers to the ratio of biomass produced to water used. **Figure 6** shows the relative WUE against the stress factor. WUE increased with increasing stress in CAM plants,

reaching up to 2.1 times that of the control. However, this reflects reduced water consumption rather than maintained or improved biomass production. In absolute terms, DM decreased with increasing stress for all species. Therefore, the higher WUE should not be interpreted as improved productivity. The regression slope of WUE vs. S for CAM plants was approximately 12 times steeper than that for *Cynodon*.

C. dactylon showed stable WUE compared to that of CAM species, reaching 1.2 at the highest stress levels. This design trade-off is important: infrequent saline watering saves water but reduces canopy cover, whereas frequent irrigation sustains biomass but increases water use. Reduced canopy cover under stress also leaves substrates more exposed to splash erosion during subsequent rainfall events (cf. **Figure 3c vs. 3d–3e**), thereby creating a feedback loop in which water-saving strategies may indirectly compromise substrate integrity.

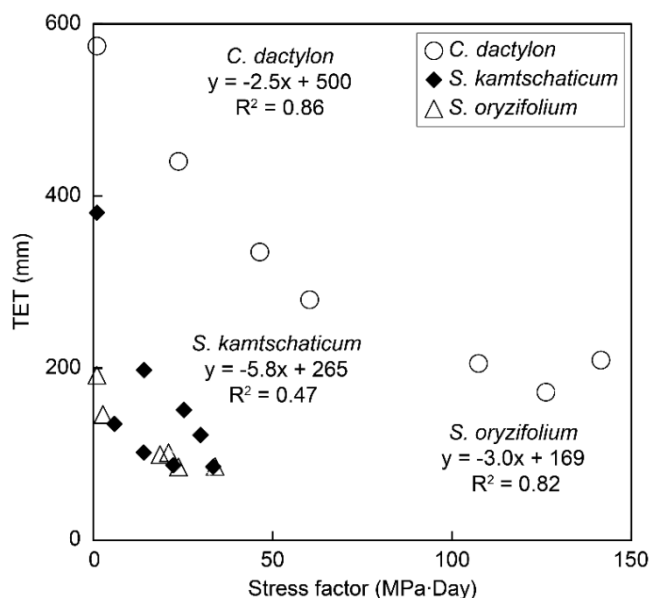


Figure 5 Relationship between stress factor and total evapotranspiration (TET) for Crassulacean acid metabolism (CAM) species (*S. kamschaticum*, *S. oryzifolium*); dashed: turf (*C. dactylon*). Linear regressions are shown

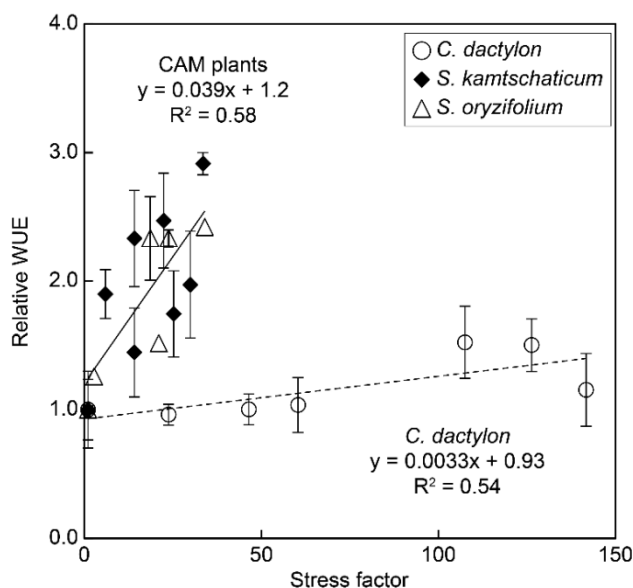


Figure 6 Relative water use efficiency (WUE) (baseline = 1.0 under frequent 0.7 dS m⁻¹). Solid lines: Crassulacean acid metabolism (CAM) species (*S. kamschaticum*, *S. oryzifolium*); dashed: turf (*C. dactylon*). Lines depict linear regressions

Salt accumulation in leaves

Leaf ion concentrations were measured to assess species-specific responses to salinity (Figure 7, frequent irrigation treatments). As expected, total cation content increased with irrigation water salinity across all species. *C. dactylon* consistently accumulated more Na^+ than the *Sedum* species, likely because of higher transpiration. However, the leaf Na^+ ratio relative to irrigation water was only 0.04-0.21, indicating that all species excluded most salt [25].

Potassium remained the dominant cation under all conditions [26]. Under stress treatments, the CAM plants maintained approximately 1.9-2.1 times higher K levels than the grass. *S. kamtschaticum* showed tissue damage under some high-salinity treatments, possibly because of temporary CAM cycle breakdown. In contrast, *S. oryzifolium* appeared to avoid this by rapidly entering dormancy as stress intensified.

ECleaf was proportionally correlated with total cation content. However, CAM leaves showed only 28%-55% of the EC values of grass leaves. ECleaf serves as a relative indicator of tissue salt loading rather than an absolute stress threshold. Its relationship with physiological endpoints requires species-specific calibration. Factors such as tissue water content, leaf age, and seasonal variation may affect ECleaf values independently of actual salt stress. Therefore, we recommend using ECleaf as a screening tool in conjunction

with visual assessment, rather than as a standalone diagnostic.

Salinity stress may indirectly affect pollinator communities, primarily through reduced floral resource quantity: salt-stressed plants produce fewer flowers, smaller floral displays, and less nectar. A recent review [7] noted the lack of studies on direct salinity–pollinator effects; the effects are most likely mediated through changes in plant chemistry and floral resource provision. Water stress, which often co-occurs with salinity, substantially reduces nectar volume in bee-pollinated species [27]. These indirect effects reinforce the importance of maintaining substrate salinity at tolerable ranges.

Over multiple seasons, cumulative salt deposition during dry periods may progressively alter substrate chemistry, even with monsoon leaching. Long-term salt accumulation could shift species composition toward more halophytic communities [28, 29], and substrate organic matter decomposition may alter water-holding capacity. Plant succession, including gradual dominance of stress-tolerant species, could reduce floral diversity if not actively managed. Furthermore, repeated wetting–drying cycles combined with salt crystallization may degrade substrate physical structure, thereby increasing susceptibility to erosion during subsequent rainfall.

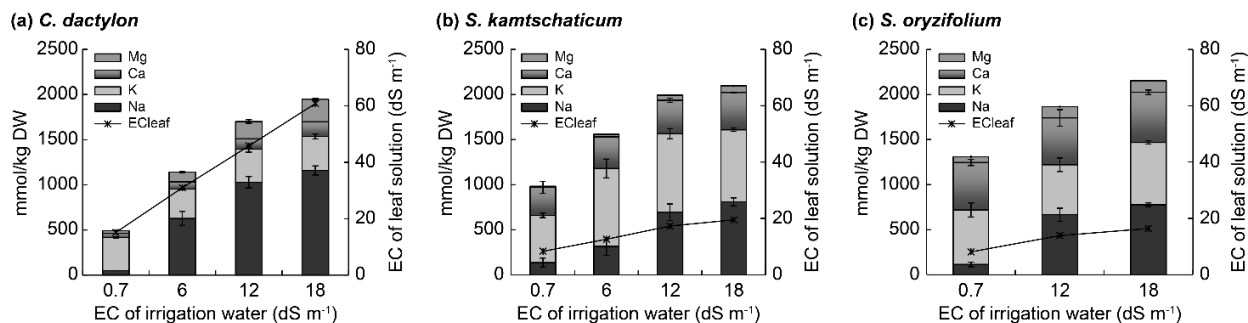


Figure 7 Leaf cation concentrations (Mg^{2+} , Ca^{2+} , K^+ , and Na^+) and EC under frequent irrigation at different salinity levels; DW = dry mass

Operational strategy matrix for Thai monsoon roofs

Green roof irrigation and management strategies vary globally. Thailand faces a pronounced monsoon rhythm: a long, hot and dry season followed by months of heavy rainfall. This seasonality directly shapes rooftop vegetation.

We constructed a 2×2 operational strategy matrix to facilitate the applicability of our experimental findings (**Figure 8**). This matrix is a conceptual synthesis derived from experimental observations and has not been field-validated. Thus, it should be treated as a decision-support heuristic rather than a prescriptive protocol.

A practical rule is to anchor in a Passive Habitat quadrant during the monsoon season and then carry a Resilient Base during the dry season. In the Passive Habitat quadrant (Rainy/Fresh $\times$ Low operation), native wildflowers thrive with rainfall alone; clearing of gutters or drains is often sufficient to prevent waterlogging. The splash erosion results (**Figure 3**) underscore the importance of this drain maintenance: substrate particles detached by monsoon rainfall can accumulate in drainage outlets, and even moderate vegetative cover may not fully prevent splash-driven particle transport (**Figure 3d**). Therefore, regular drainage checks serve a dual purpose—prevention of waterlogging and removal of eroded substrate material that could obstruct water flow. If resources are sufficient, managers can move upward into the High Diversity or Intensive Care quadrants to enrich flowering. Nonetheless, the system remains functional and pollinator-supportive even without such inputs.

Although CAM species provide reliable green cover during drought, their reduced growth rate and suppressed flowering under stress may limit nectar and pollen availability. Consequently, an all-CAM roof may sustain vegetation but underperform as a pollinator habitat during extended dry periods. Thus, mixed plantings with stress-tolerant flowering herbs are recommended.

Although designed for Thailand's monsoon seasonality, the matrix logic is transferable to other climates. Practitioners in other monsoon or semi-arid climates can map their local dry and wet seasons onto the

horizontal axis and adjust the species palette to locally available drought- and salt-tolerant species.

Limitations and future directions

This study had some limitations. First, experiments were conducted on pot-scale micro-green roofs in a glasshouse. Actual rooftop dynamics (wind, rainfall, and advection) may alter drying, leaching, and heat loads. At full-roof scale, wind exposure would accelerate substrate drying and deposit salt on foliage. Furthermore, heterogeneous substrate depths would create spatial variability in moisture and salinity regimes. Substrate erosion, which is absent in pot experiments, becomes a significant concern at full scale. As demonstrated in the companion experiments (**Figure 3**), raindrop splash can detach and displace substantial amounts of substrate material from thin green roof media, particularly under incomplete vegetative cover (**Figure 3c–3d**). Therefore, maintaining adequate canopy cover through appropriate irrigation management serves both a habitat function and an erosion-control function.

Second, reclaimed water was modeled using diluted seawater to isolate ionic effects. Actual reclaimed water typically contains residual nutrients (N and P), dissolved organic matter, and microbial communities that may alter growth and salt transport. The ionic composition also differs: reclaimed water generally has higher Ca^{2+} and HCO_3^- relative to Na^+ than seawater. Therefore, future studies should validate these findings using actual treated wastewater.

Third, the stress factor (S) used general agronomic thresholds (pF 3.0 [14, 18]) that may not capture species-specific responses. Thus, future studies should validate S against leaf water potential and stomatal conductance. Furthermore, leaf-extract EC was only used as a proxy of tissue salinity, consequently necessitating calibration across species.

Fourth, the species palette was narrow, the trial was short, and flowering/pollinator visitation were not measured. Therefore, pollinator-habitat inferences remain conceptual. Conclusions on pollinator habitats are based on the assumption that sustained vegetative cover serves as a prerequisite for subsequent floral resource provision.

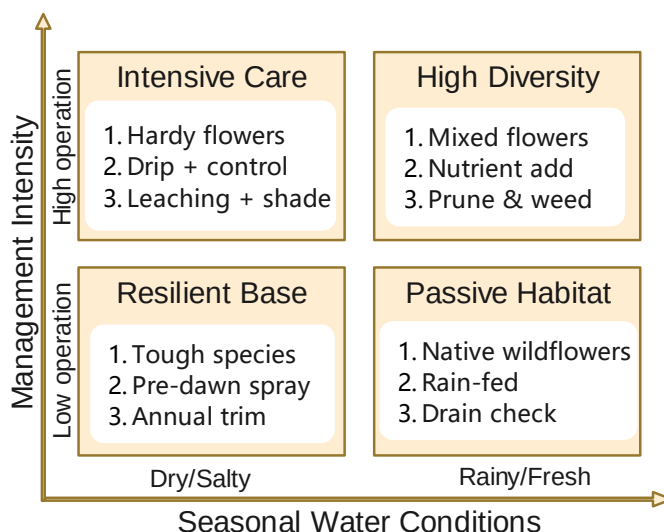


Figure 8 Operational strategy matrix for pollinator-friendly green roofs under monsoon climates:
A conceptual framework linking seasonal water conditions and management intensity

Urban rooftop environments also subject plants and pollinators to additional stressors that were not simulated in the present study. These include reflected thermal radiation, urban heat island effects, and air pollutants (e.g., NO_x , particulate matter), which may interfere with floral scent signals that are important for pollinator navigation.

Future studies should test full-scale roofs across Thai dry/rainy seasons using reclaimed water (with rainwater blending), validate S and EC proxies against plant water potentials, expand to native Thai wildflowers, track flowering phenology and pollinator visitation, and compare drip vs. micro-spray with planned leaching to maintain year-round habitat while minimizing water use.

Conclusions

The synergy of a suitable substrate, resilient plants, climate-responsive design, and smart irrigation control can produce green roofs that use minimal water while sustaining diverse vegetation for urban pollinators. Our research shows that certain plants can adapt under saline and limited water inputs by reducing their water use and tolerating moderate salt accumulation. Beyond habitat provision, maintaining vegetative cover also protects thin substrates from splash erosion, linking irrigation management to

long-term substrate integrity. Urban designers can develop environmentally sustainable and ecologically beneficial green roofs by harnessing these natural adaptations and complementing them with thoughtful engineering. However, the pollinator-habitat benefits inferred in this study remain conceptual, as flowering and pollinator visitation were not directly observed. Future studies should refine this approach by testing herbaceous species and wildflowers that attract pollinators. Nonetheless, our findings provide a foundation for the advancement of such designs, bringing us closer to green roofs that function as urban oases for biodiversity while conserving fresh water.

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