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Integrating NbS in compact city renewal: Preferences, constraints, and opportunities☆

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ABSTRACT

Compact cities, often being praised for their sustainability advantages, face significant urban challenges (UC) due to their dense configurations and the intensifying effects of climate change. This study, conducted in Hong Kong, investigates the potential of using Nature-based Solutions (NbS) to mitigate these issues through a dual methodology—integrating surveys capturing public and professional perceptions and a novel geoinformatics analysis assessing spatial opportunities. The survey engaged 233 residents and 36 experts and found that climate change ranks as a primary concern, surpassed only by housing shortages. Residents favored NbS benefits, whereas experts prioritized ecological gains like biodiversity enhancement. Both groups, however, noted potential drawbacks including risks of animal-borne diseases and nuisances. The geoinformatics analysis evaluated nine sampling areas across three regions and identified rooftop retrofitting as a key strategy for expanding NbS coverage. Vertical greening on walls and linear infrastructure also emerged as viable methods to expand NbS. With these measures, the total NbS coverage could increase from about 15–20 % to more than 30 % in the analyzed areas. By synthesizing public preferences with spatial feasibility, this study develops a comprehensive framework for NbS deployment in compact urban environments. This dual approach bridges a critical gap in conventional urban planning by ensuring solutions are both socially relevant and technically sound.

1. Introduction

Compact city has become the "*central paradigm of urbanism* (Bibri et al., 2020)." A compact city is characterized not only by high population density but also by vibrant central areas, mixed-use development, convenient public transportation, and easy access to services and jobs (Gary, 2023; OECD, 2012). It has advantages over a sprawl city in many aspects, including efficient land use, short commute time, and high usage rates of public infrastructure and transport systems (Gary, 2023). Hong Kong is an example of a compact city, where 7.5 million people live in 35 % of the developed areas (Wong, 2022). Conversely, the protected areas occupy 40 % of the total land surface in Hong Kong (HKAFC, 2024), and there are additional "buffer" zones between the protected areas and developed ones. In this compact city, more than 12 million passenger trips are taken daily through public transport systems, accounting for over 90 % of the total passenger trips (HKTHB, 2017). Compared to a sprawl city of a similar population size and development level, a compact city has a significantly smaller footprint in terms of land use and greenhouse gas (GHG) emissions.

However, even a compact city faces various urban challenges (UC), especially amid global climate change and resulting weather extremes. In certain aspects, challenges in compact cities are even more daunting than those in sprawl ones. For instance, the compact urban form exacerbates heat island effects due to blocked ventilation and heat

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absorption by buildings and infrastructure (Hong et al., 2023; Zhou et al., 2017), raises flooding risk due to extensive impermeable surfaces (Balaian et al., 2024), increases water and air pollution due to intense anthropogenic activities (Yuan et al., 2021; Mansfield et al., 2015), and lacks green space due to high coverage of buildings and infrastructure (Tappert et al., 2018). Such stresses threaten residents' health and well-being (Huang et al., 2020; Twiddy et al., 2022; Zhu and Lu, 2023).

Nature-based Solutions (NbS) have emerged as alternative or complementary approaches (of grey infrastructure) to addressing UC. There are variations in the definition and set of NbS (Castellar et al. 2021). According to the European Commission (2015), NbS refers to "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions". According to International Union for Conservation of Nature (IUCN) (Cohen-Shacham et al., 2016), NbS is defined as "actions to protect, sustainably manage, and restore (create) natural or modified ecosystems that address societal challenges (including urban ones) effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits". As can be seen, the EC definition highlights solutions based on or inspired by nature, aiming to achieve broader sustainability goals, while the IUCN definition emphasizes ecosystem conservation so that both human societies and wildlife can benefit from ecosystem services (ES). Several comprehensive studies (e.g., Almenar et al., 2021; Castellar et al., 2021; Debele et al., 2019; Fang et al., 2023) have been conducted to identify the NbS types as well as the connections between NbS, ES, and UC. According to the study by Castellar et al. (2021), who compiled a list of NbS based on four Horizon 2020 projects and expert feedback, solutions merely inspired by nature but not "employing nature" are not listed as NbS. If nature-inspired solutions are excluded, the set of NbS by EC and IUCN may not vary significantly, although the selection criteria and priorities may still differ.

Cities are often divided into different zones with specific functions. A compact city can be planned with some areas densely populated, while others are specifically for wildlife. As a result, NbS should match the expected functions of those zones. In areas heavily inhabited by humans, undoubtedly, the priority should be focused on economic and effective solutions to UC in order to better serve the people. In protected areas, the priority may be shifted more to conservation, although certain ES offered by the protected areas also benefit urban residents indirectly or in the long term. In buffer zones, a mixed approach may be taken to balance the needs of residents and wildlife. The functional differences of urban areas require varying degrees and types of nexus between UC, ES, and NbS.

However, a literature review indicates that such functional contexts are seldom considered in selecting NbS. Literature is scarce on what NbS to choose and how to incorporate them from a large number of possible options in the renewal of well-established urban areas, especially the compact ones where NbS deployment is often limited. Introducing nature into developed, compact urban areas brings both opportunities and cautions, because not all NbS types are suitable or welcomed by residents in such areas due to high space competition or some side effects of the natural processes. Examples of negative effects include falling leaves and root damage to infrastructure. Therefore, it is important to examine the set of NbS in the renewal of compact cities.

This study aims to investigate the challenges, opportunities, and strategies of integrating NbS in retrofitting compact cities—an area that has received limited attention in existing literature. It focuses on three related key research questions: (1) What NbS options are desired in compact urban areas? (2) What constraints (or capacity limits) do we encounter when implementing these desired options? (3) How can we bridge the gaps between the desirable NbS options and the constraints? These questions are specified in the following objectives: (1) to understand the UC of a compact city as perceived by individuals of diverse backgrounds; (2) to explore the preferences and perceived benefits of NbS in a compact city by individuals of diverse backgrounds; (3) to identify the constraints of implementing NbS in revitalizing well-established compact urban areas; and (4) to assess the opportunities and strategies for introducing NbS in compact built environment. This study occurs in Hong Kong, a typical compact city. To achieve objectives (1) and (2), detailed questionnaire surveys were conducted among residents and experts to elucidate their perceptions, opinions, and suggestions. This is accompanied by a quantitative analysis of typical urban areas in Hong Kong using geoinformatics analysis to identify the constraints and opportunities of implementing NbS, addressing objectives (3) and (4).

2. Methodology

This study selects Hong Kong as a representative compact city due to its high density (6,615 persons/km^2) (UN 2019) and pressing needs for sustainable urban renewal. Two main directions were taken to identify the perceptions, opportunities, and constraints of implementing NbS in established urban areas in Hong Kong. The first direction was to obtain the perceptions and opinions of two groups—residents and experts, on (1) urban challenges (UC), (2) possible NbS options to address those challenges, and (3) perceived benefits, preferences, and concerns of integrating NbS in compact urban settings. Two separate surveys were conducted among residents and experts. It was expected that these two groups of people would collectively provide a holistic view on NbS based on their living and professional experiences in compact cities. The results of the surveys could also help identify the most preferred NbS options.

Based on outcomes from the surveys, the second direction was to examine the potentials and constraints of implementing the most preferred NbS in urban areas. Samples of compact urban areas were randomly selected from a high-resolution map in Hong Kong. The current NbS types in the selected area were firstly identified. Opportunities and constraints to further increase the NbS coverage in the selected areas were analyzed and examined in detail. It is crucial to learn the gaps between preferred NbS options and feasibility of implementing such options to understand how and to what extent NbS can be employed to address UC in a compact city. The methods for these two broad approaches are introduced below.

2.1. Surveys of residents and experts

We surveyed 233 local residents through in-person interviews across various districts in Hong Kong from October 2024 to January 2025 (Refer to Appendix for survey questions). Participants were randomly selected at both NbS-equipped sites (e.g., parks) and non-NbS sites (e.g., streets) to ensure representative sampling. The questionnaire comprised three sections: (1) UC, (2) preferred NbS interventions, and (3) expected benefits and concerns of NbS. Residents rated each of nine predefined UC on a 5-point Likert scale (1 = least serious, 5 = most serious), with each challenge illustrated by three example scenarios. They then rated up to five exemplar NbS options per major category on a 5-point preference scale. Respondents also assessed the anticipated advantages and drawbacks of NbS implementation. Socio-demographic data of the respondents (e.g., gender, age, education level, income, occupation, etc.) were also recorded.

We recruited 36 professionals who are familiar with NbS (e.g., academics, government planners, non-governmental practitioners, and industry experts) to take a similar online survey. The expert survey covered the same core sections as the one given to the residents. Experts were invited from Hong Kong, mainland China, European countries, and the USA. These participants possessed expertise in NbS and had prior experience working in or visiting Hong Kong, to ensure that they are familiar with the local context. In addition, experts were asked to provide their professional background details (e.g., working sector, role,

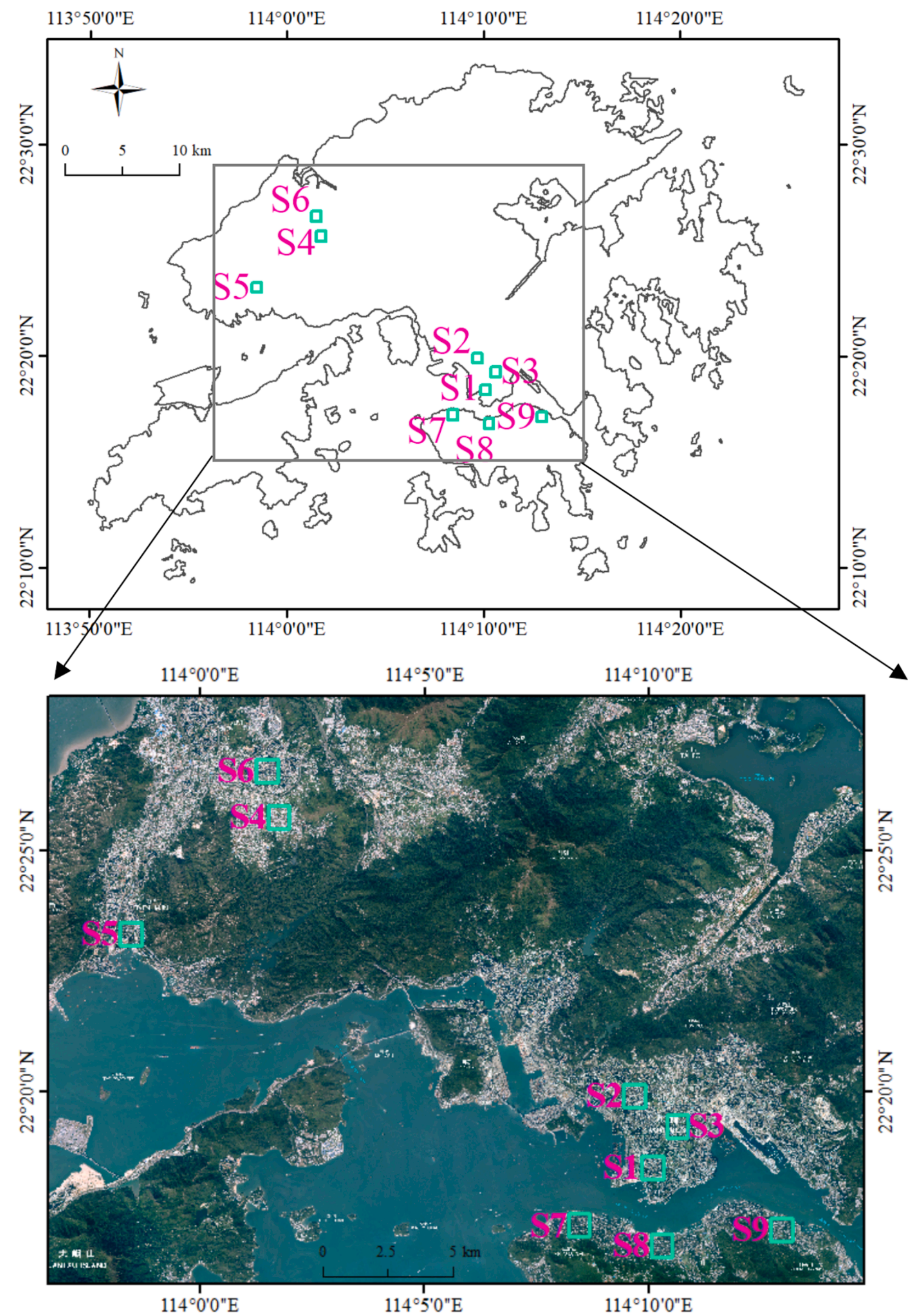


Fig. 1. Locations of the sampled areas.

geographical location, years of NbS experience, etc.).

Drawing on existing literature, we compiled a list of UC and categorized NbS into groups (e.g., Almenar et al., 2021; Castellar et al., 2021; Castelo et al., 2023; Croeser et al., 2021). We classified UC into nine major groups, including climate change impacts, urban degradation, air pollution, waste management issues, water management issues, transportation issues, housing problems, biodiversity loss, and social inequality and community resilience, as shown in Fig. A1 in the Appendix. The figure shows these major UC groups along with examples under each group, which are provided to the respondents in surveys for them to rate the severity and impact of such UC in Hong Kong.

We classified NbS types into six major categories, including building-scale interventions, linear features/routes, parks and gardens, water bodies, hybrid green infrastructure, and other non-sealed urban areas (e.g., Morello et al., 2019) (Fig. A2 in the Appendix). The detailed NbS options, with photos and explanations, were provided to survey respondents to rate their preferences for the NbS types.

2.2. Geoinformatics analysis

Through the surveys, we could identify the preferred NbS options for urban renewal. However, the feasibility and potential of such options remain unknown. Therefore, we employed geoinformatics analysis to assess the constraints and potentials of implementing NbS options in the typical cityscape of Hong Kong. Three representative sampling areas were selected from three regions in Hong Kong: Kowloon, New Territories, and Hong Kong Island (Fig. 1). The areas cover both residential and commercial zones, and each sampling area has a size of 800 × 800 m^2.

To accurately identify urban land cover types including NbS, the

Table 1
Socio-demographic variables of surveyed residents.

Demographics	No.	Proportion	Demographics	No.	Proportion
Gender			Occupation		
Male	124	53.2 %	Students	58	24.9 %
Female	109	46.8 %	Retired	37	15.9 %
Age			Unemployed	10	4.3 %
0–14 years old	4	1.8 %	Monthly personal income		
15–29 years old	76	32.6 %	< 10,000 HKD	99	42.5 %
30–44 years old	81	34.8 %	10,000–29,999 HKD	63	27.0 %
45–59 years old	28	12.0 %	30,000–49,999 HKD	38	16.3 %
60–74 years old	36	15.5 %	50,000–69,999 HKD	20	8.6 %
>74 years old	8	3.4 %	> 70,000 HKD	13	5.6 %
Education level			Residency duration		
High school or below	82	35.2 %	Not live in Hong Kong	3	1.3 %
Associate degree	20	8.6 %	0–10 years	19	8.2 %
Bachelor's degree	89	38.2 %	10–20 years	27	11.6 %
Master's degree	36	15.5 %	20–30 years	56	24.0 %
Doctoral degree	6	2.6 %	> 30 years	128	54.9 %
Occupation			Apartment ownership		
Working	111	47.6 %	Renting	116	49.8 %
Homemaker	17	7.3 %	Owning	117	50.2 %

Table 2
Experts' years of experience and professional roles.

Year of experience	No.	Proportion	Professional roles	No.	Proportion
<5 years	9	25 %	Researchers	27	75 %
5–10 years	6	16.7 %	Urban planners/managers	10	27.8 %
10–20 years	12	33.3 %	Designers	8	22.2 %
20–30 years	5	13.9 %	Consultants/technical service professionals	6	16.7 %
>30 years	4	11.1 %	Policymakers	5	13.9 %
			Investors	2	5.6 %

Note: Due to the interdisciplinary nature of NbS, experts could select multiple professional roles.

Urban-Seg, a semantic segmentation model built on the FP16-ViT-B-32 backbone, was employed in this study (https://github.com/anxiangsir/urban_seg). The backbone is a Vision Transformer (ViT) (Dosovitskiy et al., 2021) model optimized using Union (An et al., 2023), a vision-language model training framework that incorporates sample-to-cluster contrastive learning and a joint visual-textual classification loss function to enhance model generalizability and reduce label ambiguity (An et al., 2025). Urban-Seg integrates a decoder module that comprises five upsampling blocks to reconstruct a feature tensor matching the input image size (224 × 224 pixels) (Fig. A3 in the Appendix), and an output layer that classifies each pixel into one of five categories: vegetation, road, building, water, or others.

The model was trained on an NVIDIA RTX 3080 GPU using 10,000 labeled remote sensing images. We adopted the AdamW optimizer with a linear learning rate decay schedule: 0.00001 for the ViT backbone and 0.0005 for the Urban-Seg head. A batch size of 32 was used, resulting in approximately 312 steps per epoch. The model was trained until it reached over 20,000 steps, corresponding to 65 epochs. Training loss convergence is shown in Fig. A4 in the Appendix. When evaluated on an independent high-resolution test image of size 3357 × 6116 pixels, the model achieved an average classification accuracy of 85.48 %, with vegetation class accuracy reaching 86.19 %.

The trained Urban-Seg model was subsequently used for automatic classification of NbS land types across nine 800 × 800 m^2 representative developed areas (Fig. 1). Classification was initially performed on 0.25 m resolution True Digital Orthophoto (TDOP) imagery from November 2023 (https://portal.csdi.gov.hk/). Subsequently, complementary datasets, including 10 m resolution land use data (https://www.pland.gov.hk/pland_tc/info_serv/open_data/landu/) and building footprint vector layers, were integrated to refine road, building, and other land cover classifications. Building footprints were rasterized at 0.25 m resolution to correct and improve building class accuracy. Based on the spatial overlap of vegetation, buildings, roads, and other land types, we identified three NbS land types: (1) NbS A: Building-scale interventions (e.g., green roofs), (2) NbS B: Linear corridor-type interventions (e.g., street trees), and (3) NbS C: Park- and garden-type interventions. The other types are uncommon in the chosen areas and hence not included. The full classification workflow is shown in Fig. A5 in the Appendix.

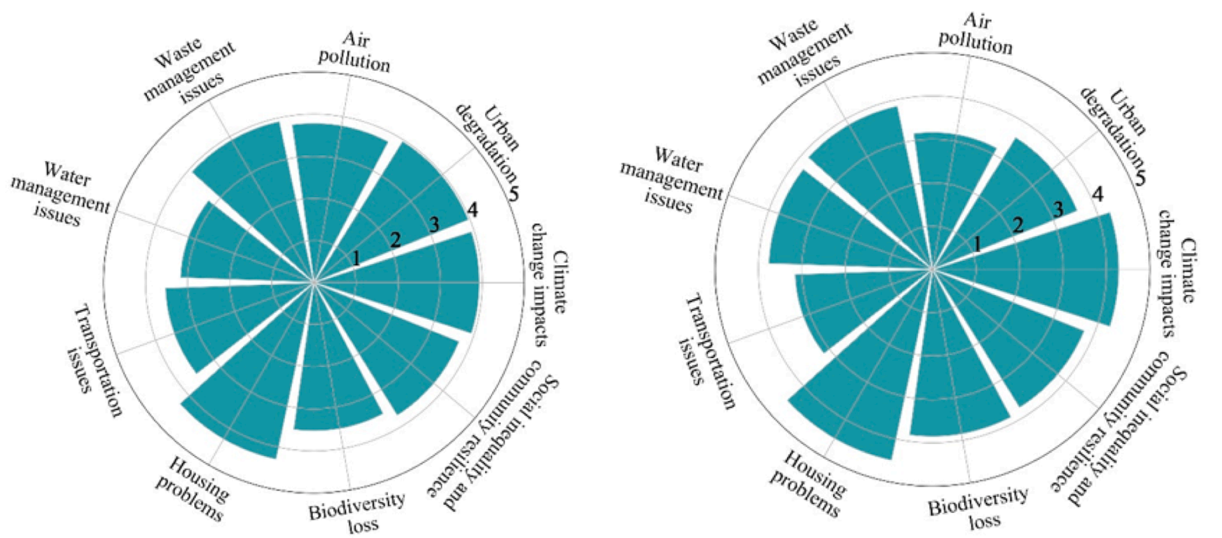
Apart from identifying existing NbS applications, we also identified urban surface areas with potential for future NbS implementation. Since typical rooftop features such as green roofs and rooftop gardens can be visually inferred from orthophotography imagery. To facilitate the large-scale identification of green roof feasibility, we trained a Support Vector Machine (SVM) classifier to categorize rooftops into two groups: (1) potentially developable into NbS Type A, and (2) not suitable (already developed or occupied rooftops). Due to the lack of detailed rooftop annotations in existing datasets, expert-defined positive Regions of Interest (RoIs) were manually labeled on each TODP image. These RoIs were then used to extract pixel-level RGB features and train the SVM model, which achieved an average classification accuracy of 75.35 % on the test stage. For NbS types that are difficult to automatically process from orthophotography imagery, a focus group was formed to manually examine their possible deployment. Examples of such NbS include vertical greening, street trees in a small plot, and narrow green corridors. The focus group examined the vacant spaces in 3D real-world city models and discussed the potential of implementing the most proper NbS based on site constraints. The areas to implement the chosen NbS were marked and summarized for further analysis.

3. Results

3.1. Respondents' information

The socio-demographic information of the 233 surveyed residents is summarized in Table 1. As shown in the Table, the gender distribution is nearly balanced, with males slightly exceeding females. The age of the respondents approximately follows a normal distribution, with young and middle-aged ones constituting the majority (69.2 %). In terms of education, the majority (64.9 %) of the respondents have an associate degree or above. Most of the respondents are either employed or students. The monthly income of the respondents tilts to the lower end because a large proportion of them are students. In addition, the majority (78.9 %) of the respondents have lived in Hong Kong for more than 20 years; therefore, they are familiar with local conditions and UC. Home ownership is evenly split, with 50.2 % owning their apartments and 49.8 % renting. Note that home ownership in Hong Kong is about 51.2 % (Hui, 2022). Therefore, the home ownership rate among survey respondents closely mirrors the average ownership rate in Hong Kong, making their perspectives representative of the general public's views on living conditions and environments.

The survey was also conducted among a panel of 36 invited experts through an online survey. Geographically, the invited experts were distributed as follows: 61.1 % were based in mainland China, 27.8 % in Hong Kong, and 8.3 % in European cities and 2.8 % in the USA. Of the respondents, about 75 % have more than 5 years of experience and 58 % have over 10 years of experience. The invited experts demonstrated a broad spectrum of professional experience related to NbS, including researchers, urban planners and managers, designers, consultants/technical service professionals, policymakers, and investors (Table 2).



(a) Residents' perception of urban challenges (b) Experts' perception of urban challenges

Fig. 2. Stakeholders' perceptions of urban challenges.

Table 3
Key demographic variables affecting residents' perceptions of urban challenges.

Urban challenges	Gender	Age	Education level	Residency duration
Climate change impacts	–-	0.329^{+} (<0.001^{++})	0.250 (0.003)	–-
Urban degradation	–-	–-	0.193 (0.024)	–-
Air pollution	–-	0.171 (0.049)	–-	–-
Waste management issues	–-	–-	0.207 (0.013)	0.206 (0.010)
Water management issues	–-	0.246 (0.004)	–-	–-
Transportation issues	–-	–-	–-	0.162 (0.050)
Housing problems	0.161 (0.014)	–-	0.222 (0.009)	–-
Biodiversity loss	–-	0.208 (0.016)	0.202 (0.018)	–-
Social inequality and community resilience	–-	–-	–-	–-

+: Standardized Coefficients Beta (β).
++: p value.

3.2. Perceptions of urban challenges (UC)

Fig. 2 illustrates the perceptions of UC in Hong Kong by residents and experts. Residents identified housing problems as the most critical issue (mean = 4.3), followed by urban degradation, climate change impacts, and waste management (Fig. 2(a)). Air pollution, social inequality and community resilience, transportation issues, and biodiversity loss received relatively less attention. Notably, water management was perceived as the least concerning challenge (mean = 3.18).

Experts also ranked housing problems as the most severe issue (mean = 4.53), followed by climate change impacts (mean = 4.28) (Fig. 2(b)). The average scores for these two issues are distinguishably higher than the others. Waste management, biodiversity loss, social inequality and community resilience, water management, and urban degradation were rated similarly. Conversely, air pollution (mean = 3.19) and transportation issues (mean = 3.17) were seen as the least pressing challenges.

Overall, both residents and experts prioritized housing problems, climate change impacts, and waste management. Indeed, these three problems are the most pressing UC in Hong Kong. Apart from these three UC, residents expressed greater concern about air pollution compared to experts, while experts were more focused on biodiversity loss than residents.

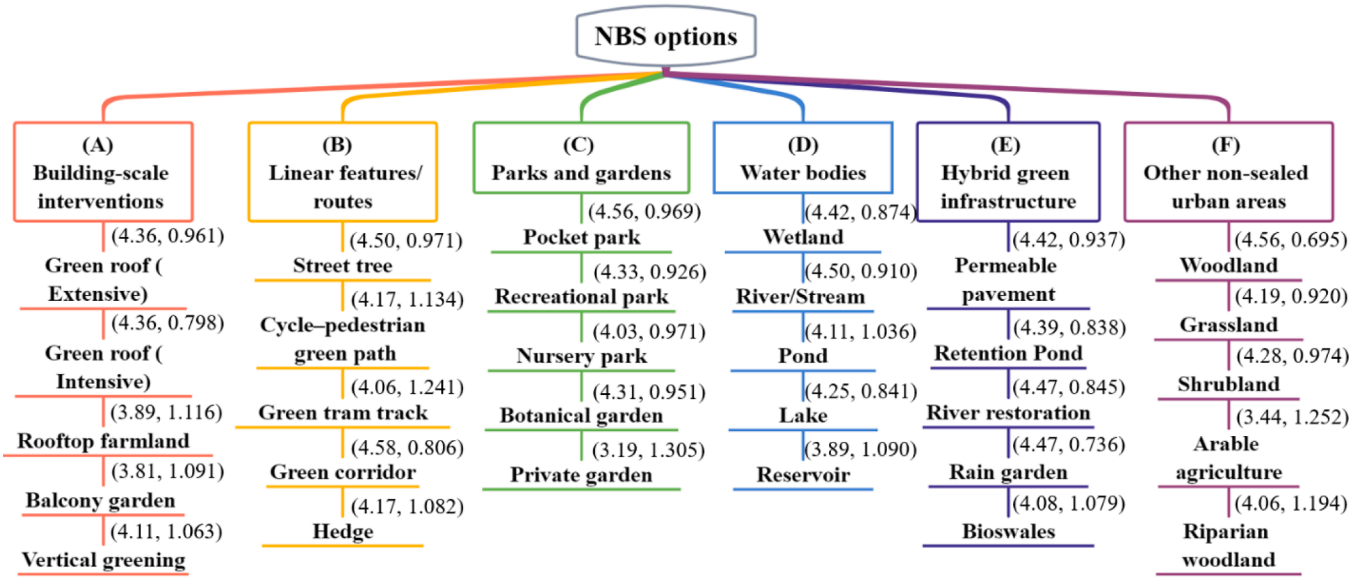
A regression analysis was conducted to examine correlations between the perceived UC and residents' socio-demographic information, with each UC serving as a dependent variable and variables in Table 1 as independent variables. Regression analysis was not performed for the expert group due to the small sample size and lack of demographic data.

Partial regression results are summarized in Table 3. Note that all the models are significant at the 0.05 significance level except for model 6 (transport issues, $p = 0.053$) and model 9 (social inequality and community resilience, $p = 0.057$). Because the p values of the insignificant models are close to the threshold, they are also listed for the interest of completeness. Additionally, only significant ($p <= 0.05$) dependent variables are shown in the table.

Table 3 indicates that gender influences perceptions of housing problems, with females expressing greater concern. Age is positively correlated to several UC: climate change impacts, air pollution, water management issues, and biodiversity loss. It appears that elderly respondents are more concerned about these issues, likely due to their long-term exposure to urban development and the resulting consequences. Education level is also positively correlated to most of the UC (5 out of 9), implying that education increases residents' awareness of the UC. In addition, residency duration is positively correlated to two UC: waste management and transportation. Note that waste management is becoming more and more challenging for Hong Kong due to the lack of landfill spaces and car ownership has been continuously increasing. Such changes are likely experienced by the respondents who stayed in Hong Kong for a longer time.

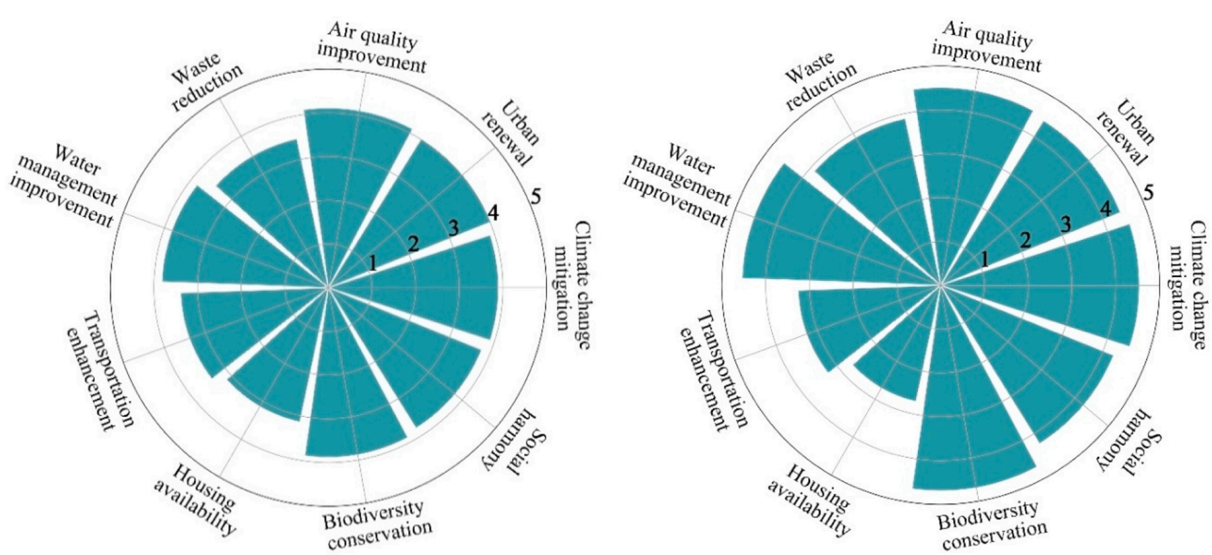
3.3. Preferences of NbS options

Fig. 3(a) illustrates the average score and standard deviation of each NbS option assigned by the residents. For building-scale interventions, residents showed a strong preference for extensive green roofs, followed by vertical greening and intensive green roofs. Conversely, rooftop farming received the lowest rating, likely due to concerns about the limited loading capacity of existing buildings. For linear features/routes, street tree was the most preferred option, followed by green corridor and cycle-pedestrian green path. The green tram track received the lowest



(b) Experts' preferences for NbS interventions to address urban challenges

Fig. 3. Residents' and experts' preferences for NbS interventions to address urban challenges.



(a) Residents' perceptions of NbS benefits (b) Experts' perceptions of NbS benefits

Fig. 4. Perceptions of the benefits of integrating NbS in Hong Kong.

ranking in this category, likely due to the limited availability of trams and shared roads between trams and cars. For parks and gardens, recreational parks ranked the highest, followed by botanical gardens and nursery parks. Private garden is the least favored in this category due to limited land resources.

In general, incorporating NbS categories (D), (E), and (F) in established compact cities is difficult because most of the options under these categories either require the creation of water bodies or the use of large land areas. Creating new water bodies would require extensive excavation and the modification of existing drainage systems. Nevertheless, the most preferred option for water bodies is a lake, a relatively large water body. The most preferred option for hybrid green infrastructure is river restoration. In the urban areas of Hong Kong, many existing rivers have been converted to concrete drainage channels (nallahs). This again reflects the residents' realistic consideration of introducing NbS into cities by upgrading existing grey infrastructure, but not creating new infrastructure. The most preferred option for other non-sealed urban areas is grassland, as it can provide recreational opportunities for residents.

If all the options of the six categories are considered together, the top three options ranked by the residents are street tree (mean = 4.19), recreational park (mean = 4.08), and botanical garden (mean = 3.96). Such options not only reveal the overall preferences of the urban residents but also reflect some realistic considerations of the constraints arising from compact environment.

Fig. 3(b) presents the experts' preferences for NbS to address UC.

Table 4
Demographic variables affecting residents' perceptions of NbS benefits.

NbS benefits	Age	Education level	Apartment ownership
Climate change mitigation	0.251+ (0.004++)	0.249 (0.004)	–
Urban renewal	–	0.167 (0.048)	0.221 (0.001)
Air quality improvement	–	–	0.136 (0.048)
Waste reduction	0.283 (0.001)	–	–
Water management improvement	0.198 (0.023)	–	–
Transportation enhancement	0.261 (0.003)	–	–
Housing availability	0.193 (0.025)	–	–
Biodiversity conservation	–	0.208 (0.014)	0.242 (<0.001)
Social harmony	–	–	–

+: Standardized Coefficients Beta (β).
++: p value.

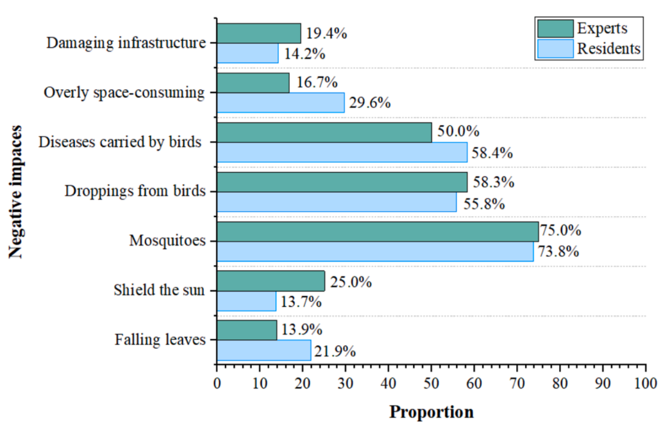


Fig. 5. Experts' and residents' concerns on NbS implementation.

Overall, the ratings provided by the expert group are higher than those provided by the residents, indicating stronger preferences of NbS by the expert group. For building-scale interventions, experts demonstrated a strong preference for extensive and intensive green roofs, followed by vertical greening. In the category of linear features/routes, green corridor and street tree were the most preferred options. Among parks and gardens, pocket parks ranked the highest, followed by recreational parks and botanical gardens.

For water bodies, river/stream emerged as the most preferred option, closely followed by wetland. In terms of hybrid green infrastructure, river restoration and rain garden ranked the highest, closely followed by permeable pavement. For other non-sealed urban areas, woodland showed a strong preference, a feature providing more intensive ecosystem services in heat reduction and flood control than others.

If all the options across the six categories are considered, the top three options ranked by the expert groups are green corridor (mean = 4.58), pocket park (mean = 4.56), and woodland (mean = 4.56). These options share some similar features with the top three options (street tree, recreational park, and botanical garden) provided by the residents. Possible reasons behind the differences will be discussed in Section 4.

3.4. Perceived benefits and concerns of implementing NbS

Fig. 4 illustrates stakeholders' perceptions regarding the benefits of implementing NbS in compact urban areas. Residents ranked air quality improvement as the most significant benefit (mean = 4.11), closely followed by urban renewal (regeneration) (mean = 4.01) (Fig. 4(a)), indicating a prioritization of enhanced living conditions. Other benefits that received moderately high ratings include: climate change mitigation (mean = 3.90), biodiversity conservation (mean = 3.88), water management improvement (mean = 3.82), and social harmony (mean = 3.79). In contrast, waste reduction (mean = 3.48), transportation enhancement (mean = 3.39), and housing availability (mean = 3.14) were perceived as comparatively less critical.

Experts identified biodiversity conservation as the most beneficial (mean = 4.69). Climate change mitigation, air quality improvement, and water management improvement were equally ranked (mean = 4.53) (Fig. 4(b)). Urban renewal (mean = 4.42) and social harmony (mean = 4.28) were also highly prioritized. In contrast, waste reduction (mean = 3.86) and transportation enhancement (mean = 3.25) received moderate importance ratings, whereas housing availability was perceived as the least significant benefit (mean = 2.72).

The correlations between the perceived NbS benefits by residents and their demographic information were also analyzed and shown in Table 4. As shown in the table, age is positively and significantly correlated to five of the nine NbS benefits, indicating that elder respondents are more in favor of using NbS to address UC, perhaps drawing from their longer personal experiences. In addition, education level is positively and significantly correlated to the three NbS benefits, likely because higher educational attainment fosters recognition of sustainability contributions by NbS. Apartment ownership is positively and significantly correlated to three NbS benefits—likely due to their vested interest in property value and neighborhood quality. It appears that the demographic backgrounds of the residents affect their perceived benefits of NbS.

Fig. 5 illustrates the concerns of residents and experts regarding the implementation of NbS in compact urban areas. Respondents were given multiple choices. Overall, both groups expressed similar concerns. The most significant issue identified was mosquitoes, with 73.8 % of residents and 75 % of experts indicating this as a primary concern.

Over half of the respondents also expressed concerns about diseases carried by mosquitoes and birds (residents: 58.4 %, experts: 50 %) and bird droppings (Residents: 55.8 %, Experts: 58.3 %). Concerns on other NbS-related issues are far less than the primary three concerns.

3.5. Land use baseline

Fig. 6 displays the TDOP images and the land types of the nine sampling areas identified through geoinformatics analysis. Each sampled area is categorized into six land types: building, road, NbS class A, NbS class B, NbS class C, and other areas. The areas occupied by each land type are shown in Table 5. Note that vertical greening was not counted in the analysis, as vertical greening is not common in Hong Kong.

As shown in Table 5, buildings and roads occupy high proportions of urban land, which also vary with district. In the three sampled areas in Kowloon, buildings and roads cover an average of 71.8 % of the land. In the sampled area S2 in Kowloon, the two land types cover 85.7 % of the land. In contrast, the three NBS categories collectively cover about 15.4 % of the land on average. In the sampled areas in New Territories, buildings and roads cover an average of 47.1 % of the land, with the three NbS categories taking an average of 22.7 % of the land. In the sampled areas in Hong Kong Island, buildings and roads cover an average of 67.8 % of the land, with the three NbS categories taking an average of 19.0 % of the land. Compared to buildings and roads, NbS only cover a small portion of land. This highlights the need to increase NbS coverage if we want to use ecosystem services to address UC. Of the three NbS types, Class C (parks and gardens) has the highest proportion.

3.6. Potential increases in NbS

The previous section indicates that the current NbS coverage is quite

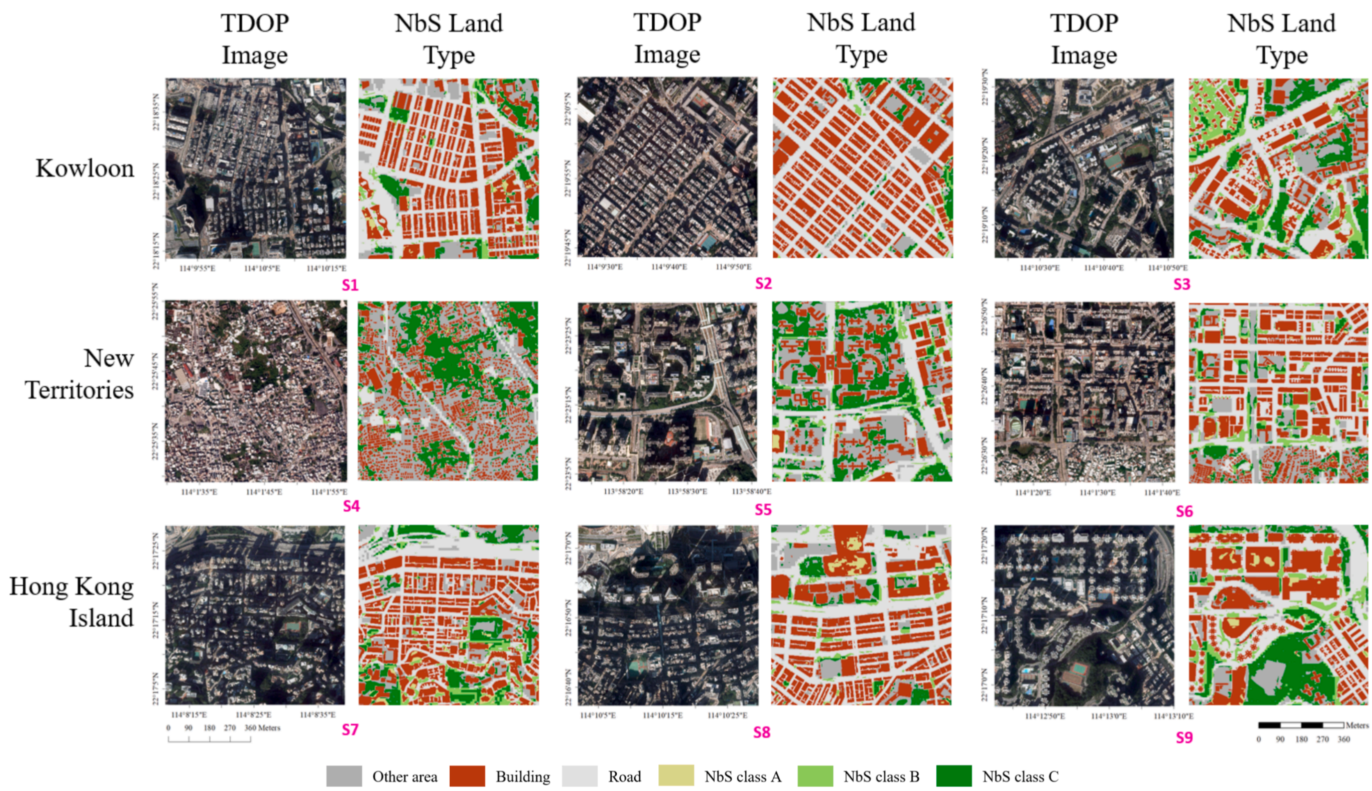


Fig. 6. Landscape of the nine sampling areas.

limited in the typical urban areas of Hong Kong. The methods introduced in Section 2.2 were used to evaluate the potential areas that can be converted to NbS in urban renewal. The potential areas that can be retrofitted to NbS are shown in Fig. 7, and the detailed analysis data is shown in Table 6.

Table 6 indicates that, on average, more than 10 % of the land covers in the sampled areas can be potentially converted to NbS. In the three sampled regions, the potential proportions are 16.8 %, 17.1 %, and 14.0 %, respectively. The reason for the relatively low percentage in Hong Kong Island is that the region has more high-rise buildings, where the rooftops host a variety of equipment (e.g., air conditioning units, window cleaning machines, etc.). Overall, the total NbS coverage could increase from about 15–20 % to more than 30 %. This would bring significant changes to the existing landscape, creating huge benefits in reducing the urban heat island effect, mitigating flooding, and enhancing biodiversity.

4. Discussion

4.1. Perceptual convergence and variation

Stakeholders' perceptions of urban challenges and roles of NbS are widely discussed in literature. Such perceptions both share some similarities and vary with geographical and socioeconomic contexts. It is commonly agreed that climate change and biodiversity loss are key drivers of UC and the adoption of NbS (e.g., Frantzeskaki, 2019; Ferreira et al., 2021; Duffaut et al. 2022), although other UC such as urban degradation and lack of green spaces are also frequently cited. Some NbS types such as urban trees are commonly mentioned in literature (e.g., Conway and Yip, 2016; Gwedla and Shackleton, 2019; Ferreira et al., 2021), but preferences of NbS by stakeholders vary greatly in different studies as well as in different survey respondents within a same study. For instance, in a study on green infrastructure in New York city (Miller and Montalto, 2019), survey respondents were divided into four groups: green infrastructure (GI) practitioners and three groups of residents with different familiarity with GI. Whereas the practitioners and resident group with the greatest familiarity with GI showed the highest preferences on bioswales, the other resident groups clearly favored permeable playgrounds, parks & natural areas.

Comparing to a proliferation of literature on NbS in western countries, reported NbS studies in high-density Asian cities are relatively fewer. Hence, this study contributes to the body of knowledge of mainstreaming NbS in such cities. Some interesting observations can be made regarding the perceptions of UC by the resident and expert groups, as well as the preferences, benefits, and concerns of NbS. Both groups rated housing and climate change impacts as the top UC, reflecting the stress and vulnerability of a compact city. The preferences of NbS, however, vary greatly between the groups. While the resident group prefers more street trees, recreational parks, and botanical gardens, the expert group is more in favor of green corridors, pocket parks, and woodland. It appears that the residents rated high on NbS that have direct influences on people or provide physical and psychological benefits, while the expert group tended to value the ecological conservation values of the NbS. Moreover, the residents believe the most important benefits provided by NbS are air quality improvement and cityscape upgrade (aesthetics), while the expert group believes biodiversity conservation is the most significant benefit. On the other hand, the perceived significant negative impacts of NbS are similar, including mosquitoes, bird droppings, and pathogens carried by wildlife.

In summary, both groups agree upon the top UC and the negative impacts of NbS, based on their objective evaluation of a compact environment. However, they differ on the preferred NbS and the associated benefits. Ordinary residents tend to prioritize service, whereas experts emphasize conservation. The finding is similar to that made from the study in New York city (Miller and Montalto, 2019), even though the types of NbS are different.

4.2. Spatial constraints of NbS in compact urban areas

Challenges and constraints of introducing NbS are also extensively

Table 5
Detailed information of the nine sampling areas (m^2).

Kowloon	Sampling area	S1	S2	S3	Mean
	Building	222,927.5 (34.8 %)	265,469.6 (41.5 %)	162,399.9 (25.4 %)	216,932.4 (33.9 %)
	Road	250,698.9 (39.2 %)	282,592.6 (44.2 %)	194,721.6 (30.4 %)	242,671 (37.9 %)
	NbS class A	7,544.3 (1.2 %)	2,729.5 (0.4 %)	13,903.8 (2.2 %)	8,059.2 (1.3 %)
	NbS class B	21,200.6 (3.3 %)	9,675.3 (1.5 %)	71,986.3 (11.2 %)	34,287.4 (5.3 %)
	NbS class C	51,430.6 (8.0 %)	21,964.8 (3.4 %)	94,743.6 (14.8 %)	56,046.3 (8.8 %)
	Other area	86,198.1 (13.5 %)	57,568.3 (9.0 %)	102,244.8 (16.0 %)	82,003.7 (12.8 %)
	Sum	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)
New Territories	Sampling area	S4	S5	S6	Mean
	Building	154,965.6 (24.2 %)	135,980.4 (21.2 %)	212,215.4 (33.2 %)	167,720.5 (26.2 %)
	Road	36,433.2 (5.7 %)	138,278.2 (21.6 %)	226,847.9 (35.4 %)	133,853.1 (20.9 %)
	NbS class A	14,377.7 (2.2 %)	7,022.4 (1.1 %)	6,568.3 (1.0 %)	9,322.8 (1.5 %)
	NbS class B	6,159.9 (1.0 %)	36,212.8 (5.7 %)	37,389 (5.8 %)	26,587.3 (4.2 %)
	NbS class C	152,152.3 (23.8 %)	132,573.9 (20.7 %)	41,646.5 (6.5 %)	108,790.9 (17.0 %)
	Other area	275,911.3 (43.1 %)	189,932.2 (29.7 %)	115,332.9 (18.0 %)	193,725.5 (30.3 %)
	Sum	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)
Hong Kong Island	Sampling area	S7	S8	S9	Mean
	Building	218,905.5 (34.2 %)	236,418.8 (36.9 %)	199,992 (31.2 %)	218,438.8 (34.1 %)
	Road	210,487.9 (32.9 %)	244,722.9 (38.2 %)	191,612.4 (29.9 %)	215,607.8 (33.7 %)
	NbS class A	12,721.6 (2.0 %)	12,410.44 (1.9 %)	13,296.5 (2.1 %)	12,809.5 (2.0 %)
	NbS class B	40,245.3 (6.3 %)	24,866.3 (3.9 %)	52,509.6 (8.2 %)	39,207 (6.1 %)
	NbS class C	69,729.9 (10.9 %)	31,309.8 (4.9 %)	108,794.6 (17.0 %)	69,944.8 (10.9 %)
	Other area	87,909.9 (13.7 %)	90,271.8 (14.1 %)	73,794.9 (11.5 %)	83,992.2 (13.1 %)
	Sum	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)	640,000 (100 %)

discussed in existing studies, most of which identified the general challenges from social and management perspectives. For instance, a study of stakeholders in the Greater Montreal Area (GMA) found that most participants do not view GI improvement as a technical issue but "social collaboration and learning processes" in GI adoption (Bissonnette, 2018). A study of six European cities (Megyesi et al., 2024) found that the lack of NbS knowledge is "the most challenging issue obstructing NbS implementation." Castelo et al. (2023) found that spatial, governance, assessment, finance, and sociocultural are five main constraints of implementing NbS in urban areas. Instead of discussing the general constrains, this study focuses on the most critical physical constraint of a compact city based on novel geoinformatics analysis. Survey results from both resident and expert groups indicate housing as the most pressing UC in Hong Kong, followed by climate change impacts. To address the housing shortage, a prevalent strategy is to increase development density, such as raising the floor area ratio (FAR). As demonstrated in Fig. 6 and Table 5, the built-up areas dominate land cover. In the sampled area S2, areas covered by buildings and roads reach 85.7 %. This not only creates a challenge of allocating spaces for NbS, but also limits the types of NbS to be implemented. For instance, Fig. 8 shows an example of an urban tree planted in a densely populated community, where confined tree pits and extensive impervious surfaces contain root development and hydraulic conductivity, creating a problem for the health and stability of trees. Consequently, urban trees are found to have a short lifespan, and falling trees pose a public hazard. Conversely, both the resident and expert groups recognize that climate change impacts are a severe UC. High-density urban morphology exacerbates climate change impacts by absorbing heat, curbing air flows, and preventing the natural infiltration of stormwater. This highlights the conflicts between high-density development and NbS application. Therefore, the selection of NbS in urban renewal must consider the spatial constraint.

While residents and experts demonstrate general support for NbS interventions (Fig. 3) and acknowledge their benefits (Fig. 4), they simultaneously express concerns about potential negative impacts (Fig. 5). The predominant concern is mosquito bites, followed by infectious diseases caused by mosquitoes and birds, and issues with bird droppings. In warm and humid climates like Hong Kong, mosquitoes represent both a significant nuisance and a public health threat, as they are known vectors for diseases including dengue fever and Zika virus.

Every year, the government spends a great amount of resources on mosquito control and public awareness campaigns, and such information is also widely covered by news media. Consequently, residents worry that NbS implementation might expand mosquito breeding grounds. Similarly, avian influenza (bird flu) is also widely publicized by the media. With NbS, the possible increase in bird population and their proximity to humans create a concern among the public. Concerns about the negative impacts of NbS, especially mosquitoes, also limit the types of NbS to be implemented in densely populated areas.

The extensive building coverage in urban areas, coupled with abundant unobstructed rooftop spaces, makes green roofs an attractive option for enhancing NbS in urban renewal initiatives. As demonstrated in Fig. 7 and Table 6, existing buildings demonstrate significant retrofit potential for green roofs. However, constraints on structural capacity must be thoroughly evaluated. In Hong Kong, for instance, the design loading capacity for Class 1 buildings (floors for domestic use and residential activities) is 2 kPa for a uniformly distributed load (q_k) and 2 kN for a concentrated load or line load (Q_k) (HKBD, 2011). It is reported that the typical loadings range from 80 to 150 kg/m^2 for extensive green roofs and from 300 to 1,000 kg/m^2 for intensive green roofs (HKASD, 2007). These parameters fundamentally restrict the types of green roofs to be installed on residential buildings. Additionally, building age, structural integrity, and potential water ponding effects demand careful evaluation and design optimization. These factors collectively influence the selection of appropriate green roof types.

4.3. Opportunities for implementing NbS in urban renewal

Although introducing NbS in urban renewal faces many spatial constraints, there are numerous opportunities if the NbS can be designed and implemented 'smartly' to adapt to the existing environment. For example, Sedum species are commonly chosen as a lightweight, extensive green roof (HKTHB, 2009) (Fig. 9(a)). With a growing substrate of 8–10 cm in thickness, the loading of green roof made of Sedum lineare can be as low as 30–70 kg/m^2 (GBWINDOW.NET, 2020), well within the structural capacity of most existing buildings.

In addition, some commercial buildings and industrial buildings have high structural capacity. In particular, a large number of industrial buildings exist in the downtown areas of Hong Kong (Fig. 9(b)), with a

Fig. 7. The potential areas for NbS implementation.

structural capacity of 12.5 kPa for a uniformly distributed load (q_k) and 9 kN for a concentrated load or line load (Q_k), 6.3 times and 4.5 times of the uniform and concentrated loading capacities of residential buildings, respectively (HKBD, 2011). Greening in the industrial building zones is severely lacking at the moment, and the values and usage rates of the industrial buildings have dropped significantly due to industrial relocation. The city has attempted to revitalize the industrial buildings for commercial use. If the rooftops of such buildings can be retrofitted to intensive green roofs or botanical gardens, they may not only add ecological value but also attract visitors and create new business opportunities, helping revitalize the industrial areas.

Our ground-level analyses of sampled areas revealed vertical greening as another viable strategy for urban greening. Of various vertical greening techniques, ground-climbing plants emerge as a particularly cost-effective and easily deployable solution (Fig. 10(a)). These systems offer multiple co-benefits: (1) minimal spatial requirements for implementation, (2) improved thermal comfort through reducing radiant temperature, and (3) enhanced pedestrian experience through microclimate modification.

The spaces for ground-level parks and gardens vary with the sampling areas, as shown in Table 6. In new territories, there are still vacant lands that may be converted to parks and gardens. In Hong Kong Island, however, such a potential is close to zero. Conversely, every sampling area has walls abutting streets without any vegetation cover (e.g., Fig. 10(a)). Such walls can be conveniently converted to green walls (Fig. 10(b)). Hong Kong is known for dense pedestrian traffic. However, its hot climate, exacerbated by reflective solar radiation from the walls, creates a harsh thermal environment for pedestrians. The retrofitting of the current bare walls would enhance the walkability of the city, especially by mitigating extreme heat driven by climate change.

There are also opportunities of retrofitting linear transport infrastructure with NbS. Fig. 11(a) shows an example of retrofitting an existing road in Hong Kong with the potable container. However, the shrubs in the containers are generally in poor conditions. Fig. 11(b) shows an example of a green strip of similar width, but with more vigorous and diverse plants. The design of the planters, growth media

Table 6
Detailed information on nine potential NbS application sampling areas (m^2).

Kowloon	Sampling area	S1	S2	S3	Mean
	Green roof	81,787.	131,788.6	86,552.1	100,042.3
	Vertical greening	8,384	276	2,528	3,729.3
	Street tree & green corridor	423	18	0	147
	Park & garden	10,223	0	0	3,408
	Sum	100,817	132,083	89,080	107,327
New Territories	Sampling area	S4	S5	S6	Mean
	Green roof	63,658.1	90,491.8	128,622.8	94,257.6
	Vertical greening	2,272	640	2,588	1,833.3
	Street tree & green corridor	2,443.5	78	519	1,013.5
	Park & garden	23,625	10,233	2,588	12,149
	Sum	91,999	101,443	134,318	109,253
Hong Kong Island	Sampling area	S7	S8	S9	Mean
	Green roof	67,377.7	76,260.4	96,347.4	79,995.2
	Vertical greening	24,320	150	3,967	9,479
	Street tree & green corridor	0	132	117	83
	Park & garden	0	0	0	0
	Sum	91,698	76,542	100,431	89,557

Note: The area of street trees = the length of the linear strip of land × 1.5 m width (green belt made of street trees) (Xi et al., 2023).

Fig. 8. An example of an urban tree planted in a densely populated community.

and selection of plants can be further improved to increase the volume and diversity of such plants to provide rich ecosystem services.

Another opportunity for increasing vertical green is to introduce climbers into elevated highways, as shown in Fig. 11(c) and (d). Because the elevated highways are public property, it is more convenient for the government agencies to fully utilize such space for implementing NbS.

Despite the concerns of the public and experts on problems created by NbS (e.g., mosquitoes, pathogens, nuisances), many of these problems can be effectively mitigated through proper design strategies. For example, the planting sites and growth media can be optimized to reduce standing water and moist soils to control mosquitoes. The plants on green roofs can be optimized to attract charismatic species such as butterflies (Chen et al., 2025). Through such context-sensitive designs, the benefits of NbS will further outweigh their drawbacks in dense urban areas.

Note that the techniques mentioned above is discussed in the context of Hong Kong, including space limit, building characteristics, and climate. The specific techniques or plant types may not be universally applied to other compact cities. However, the general strategies of increasing NbS can be applied to other compact cities, including retrofitting rooftops and installing vertical greening on walls and linear infrastructure.

4.4. Synthesis and future directions

Based on connections between UC and NbS benefits reported in literature (Almenar et al., 2021; Fang et al., 2024) and findings from this study, Fig. 12 demonstrates the nexus of top-rated UC, preferred NbS by both the resident and expert groups, and feasible NbS considering various constraints. The feasible NbS can effectively address four out of six top-rated UC in Hong Kong. Areas not well addressed include housing issues (affordability and shortages) and waste management. However, NbS may help regenerate some old buildings, thereby improving the quality of living environment. One promising direction of using NbS to address waste management is to develop waste-derived artificial soils for urban greening—an area that can be explored in the future.

Apart from technical considerations, implementation of NbS in compact urban areas also rely on management solution and policy innovation. In particular, capacity building is a key element of adopting NbS. Several studies have found that lack of knowledge is a key barrier for NbS implementation (e.g., Duffaut et al., 2022; Megyesi et al., 2024; Castelo et al., 2023). The finding is also echoed in this study: Not only the general public surveyed in this study typically lacks familiarity of NbS, but guidance and methods are missing for professionals to properly apply NbS. This study covers a knowledge gap by identifying those preferred and feasible NbS types, based on which specific techniques can be developed in the future. To address the physical constraints and encourage participation from the public and private sectors, other managerial and policy tools may be considered, including regulations, incentives, taxation, community involvement, and others.

5. Conclusions

It is challenging to introduce NbS in compact cities (Kabisch et al., 2022; Mahmoud et al., 2022), especially in well-established urban areas. Through surveys from resident and expert groups, this study helps understand the perceived urban challenges and preferred NbS from

(a) Sedum species planted on a green roof (b) Prevalent industrial buildings in Hong Kong

Fig. 9. An example of an extensive green roof and industrial building zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(a) A typical wall of a building on the street (b) An example of vertical green wall

Fig. 10. An example of a bare wall and vertical green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different perspectives. It also reveals possible demographic factors that contribute to variations in the perceptions of UC and preferences of NbS by residents. However, due to spatial and physical constraints, there are significant capacity gaps between the preferred solutions and the feasible ones. Through novel geoinformatics analysis, this study also helps understand such constraints and identify those NbS options that can be mostly likely implemented. Even though this study takes place in Hong Kong, the general findings and methods can be applied to other compact urban forms. The main conclusions are drawn as follows.

1. Apart from housing issues, both resident and expert groups identify climate change impacts as a significant urban challenge for a compact city.
2. The most favored NbS options by resident groups include street trees, recreational parks, and botanical gardens, while the most favored options by the expert group include green corridors, pocket parks, and woodland.
3. The resident group highly values the NbS benefits in air quality improvement and aesthetics, while the expert group highlights their benefits in biodiversity conservation. Overall, residents focus on NbS services, whereas experts emphasize conservation.

(a) An example of green strip in an existing road in Hong Kong

(b) An example of a green strip in Zhengzhou, China

(c) Elevated highways in Hong Kong

(d) Elevated highways in Chengdu, China

Fig. 11. Opportunities for retrofitting linear transport infrastructure with NbS.

4. The perceived UC and benefits are affected by the socio-demographic backgrounds of the residents, with senior citizens and those with higher education attainment being more in favor of NbS.
5. The predominant concern of NbS is mosquito bites, followed by infectious diseases caused by mosquitoes and birds, and issues with bird droppings.
6. In the analyzed compact urban areas, the total NbS coverage could increase from about 15–20 % to more than 30 %, and the highest potential for increasing NbS is to retrofit rooftops. Vertical greening on walls and linear infrastructure also presents many opportunities for NbS implementation.

CRediT authorship contribution statement

Yang Chen: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Yuehan Dou:** Writing – review & editing, Visualization, Data curation. **Shaofen Xu:** Writing – original draft, Visualization, Software. **Faith Ka Shun Chan:** Writing – review & editing, Data curation. **Dan Chong:** Writing – review & editing, Data curation. **Bowen Chen:** Data curation. **Yuhong Wang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

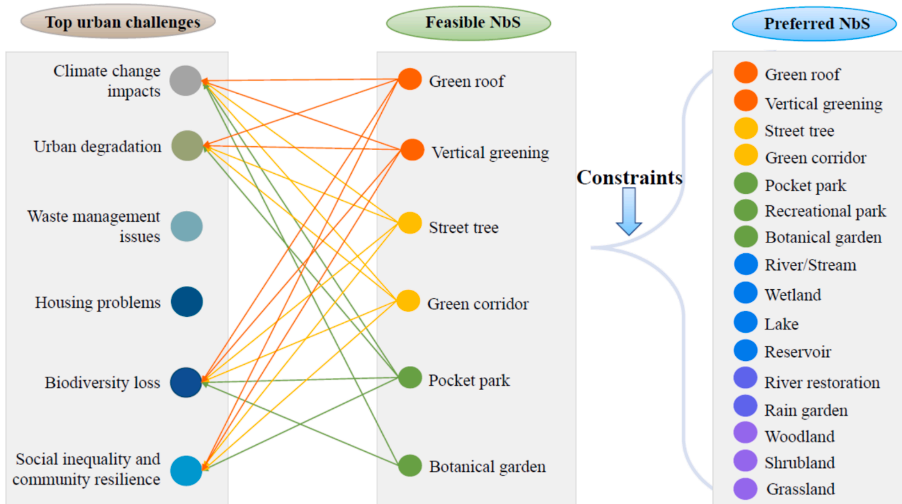


Fig. 12. The nexus of top-rated UC, preferred NbS by both the resident and expert groups, and feasible NbS considering various constraints.

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.114003.

Data availability

Data will be made available on request.

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