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REVIEW

Associations of Urban Built Environment with Cardiovascular Risks and Mortality: a Systematic Review

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Abstract With rapid urbanization, built environment has emerged as a set of modifiable factors of cardiovascular disease (CVD) risks. We conducted a systematic review to synthesize evidence on the associations of attributes of urban built environment (e.g. residential density, land use mix, greenness and walkability) with cardiovascular risk factors (e.g. hypertension and arterial stiffness) and major CVD events including mortality. A total of 63 studies, including 31 of cross-sectional design and 32 of longitudinal design conducted across 21 geographical locations and published between 2012 and 2023 were extracted for review. Overall, we report moderately consistent evidence of protective associations of greenness with cardiovascular risks and major CVD events (cross-sectional studies: 12 of 15 on hypertension/blood pressure (BP) and 2 of 3 on arterial stiffness; and longitudinal studies: 6 of 8 on hypertension/BP, 7 of 8 on CVD mortality, 3 of 3 on ischemic heart disease mortality and 5 of 8 studies on stroke hospitalization or mortality reporting significant inverse associations). Consistently, walkability was associated with lower risks of hypertension, arterial stiffness and major CVD events (cross-sectional studies: 11 of 12 on hypertension/BP and 1 of 1 on arterial stiffness; and longitudinal studies: 3 of 6 on hypertension/BP and 1 of 2 studies on CVD events being protective). Sixty-seven percent of the studies were rated as "probably high" risk of confounding bias because of inability to adjust for underlying comorbidities/family history of diseases in their statistical models. Forty-six percent and 14% of the studies were rated as "probably high" risk of bias for exposure and outcome measurements, respectively. Future studies with robust design will further help elucidate the linkages between urban built environment and cardiovascular health, thereby informing planning policies for creating healthy cities.

Keywords Built environment · Greenspace · Walkability · Hypertension · Arterial stiffness · CVD events, CVD mortality

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Introduction

Cardiovascular disease (CVD) is the leading cause of death worldwide [1]. In 2019 alone, an estimated 17.9 million people died from CVDs, accounting for over 30% of deaths globally [2]. CVDs, including ischemic heart disease (IHD) and stroke are complex chronic diseases with multifactorial aetiology and long latency. Well-known risk factors for CVDs include lifestyle and behavioural factors, including dietary habits [3, 4], cigarette smoking [5], alcohol uptake [6], hereditary influences [7], physical activity [8], sleeping quality [9] and socioeconomic status [10]. The role of gene-to-gene and gene-to-environment interactions has also been studied [11]. Among all the CVD risk markers, blood pressure (BP), a circulatory marker has been identified as a primary predictor of heart failure, atrial fibrillation and chronic syndrome disease with the strongest evidence of causation [12, 13]. In addition to BP, other hemodynamic measures such as arterial stiffness have also emerged as objective markers of cardiovascular risk and vascular ageing [14]. Stiffer arteries have long lasting arterial wall damage and relatively reduced capability to expand and contract in response to pressure changes associated with cardiac flows and have been associated with atherosclerosis, CVD events and inflammatory disorders [15]. With an increasing proportion of global population suffering from CVDs, there has been a growing number of studies examining non-pharmacological determinants of cardiovascular risk factors including BP and arterial stiffness.

Relatedly, one of the seventeen sustainable development goals (SDG) framed by United Nations pertains to “Good Health and Well-being”, with an aim to reduce one third of premature mortality from non-communicable diseases including CVDs via a mix of preventive and treatment approaches by 2030 [16]. Reducing cardiovascular risks through urban interventions is of particular importance in cities, given that urban dwellers are likely to be exposed to higher levels of adverse environmental and psychosocial stressors [17, 18]. One of the earliest studies published in 1962 found that Zulu adults who spent more time in town throughout their lifetime reported higher risk of hypertension compared to counterparts who spent a shorter period of their lives in town [19]. In the USA alone, there were 16.1 million deaths attributable to CVD over the period between 1999 and 2017, and 80% of which occurred in metropolitan settings [20].

It has been suggested that attributes of built environment in urbanized settings may constitute modifiable risk factors of CVD and CVD risks. A well-designed neighbourhood with appropriate allocations of land uses and street layout, for instance, has the potential to enable easy access to nearby services and key destinations and promote active travel, thereby enhancing physical activity [21]. Previous findings have shown the beneficial associations between residential density and cardiovascular risk factors including physical activity and obesity [22, 23]. Residential proximity to and density of green areas and public open space may promote active lifestyles, relieve stress and improve physical and cardio-respiratory fitness [24, 25]. Exposure to greenspace at standards recommended by the World Health Organization has been estimated to prevent 42,000 deaths annually in European cities [26]. Compact urban design with higher accessibility to bus stops near home and mixed land use (which increases walkable destinations compared to single land use) can also facilitate active travel, enhancing daily physical health thereby reducing cardiovascular risks [27, 28].

There has been accumulating evidence of the associations between urban environmental attributes and CVD [29, 30]. Nonetheless, existing systematic reviews have tended to focus on adiposity and related end points, synthesizing evidence primarily on physical activity, body mass index, obesity, type 2 diabetes and metabolic syndrome [25, 29, 30]. The associations of objectively measured attributes of built environment with hemodynamic measures of CVDs and specific CVD events such as stroke and IHD have remained understudied. In order to better understand underlying aetiology of CVDs and potential risk-minimizing interventions in built environment (including design, configurations and green exposure)[31], we present the first systematic synthesis of evidence of associations of objectively measured built environment exposure measures with key CVD risk factors including hypertension and arterial stiffness and major CVD events including mortality. The included studies were systematically appraised to identify potential methodological biases.

Methodology

Systematic Search and Screening

A systematic search was conducted to summarize existing evidence on the associations of urban environments with cardiovascular risk factors and major CVD events. Journal articles comprising keywords of urban environments ("built environment", "residential density", "housing density", "land use mix", "greenspace", "greenness" "walkability", "street layout", "land use", "street connectivity", "intersection density", "parks" or "sprawl") in combination with those related to key cardiovascular risk factors and events ("hypertension", "blood pressure", "arterial stiffness", "stroke", "coronary heart disease (CHD)", "myocardial infarction (MI)" or "CVD mortality") in title or abstract were searched from PubMed, Web of Science and Scopus databases with a wide collection of clinical journal articles. All references were exported to Endnote, followed by a preliminary screening based on title and abstract. Full-text articles were downloaded for further screening in reference to the selection criteria.

Inclusion and Exclusion Criteria

Studies were included for review if they (1) were in English language; (2) objectively measured attributes of residential urban built environment as exposures and (3) included CVD risk factors of hypertension, BP or arterial stiffness or major CVD events as outcomes. We restricted this review to focus only on objectively measured attributes of built environment, given that these constitute systematically measured standardized built environment exposure metrics, easily scalable and replicable in large population-based cohorts. These objectively measured attributes have been known to have inherent ability to explain spatial patterning of health [32, 33]. Review articles, abstracts and reports were excluded. With respect to study design, ecological studies (in which adjustments for individual-level confounders cannot be made) were not included in our review. Studies employing only a composite index of metabolic health as an outcome (such as metabolic syndrome involving systolic and diastolic BP (SBP and DBP), body fat, cholesterol and blood sugar) or measuring urban environment around activity spaces other than residential space (such as around schools or workplace) were also excluded. Key characteristics of the studies pooled (including authoring team, year of publication, geographic setting, study design, sample size, age, sex, outcome, exposure and findings) were entered into a predefined table and presented by study design (cross-sectional and longitudinal design).

Quality Assessment

A systematic appraisal was conducted employing the risk of bias rating tool adopted by the National Toxicology Program's Office of Health Assessment and Translation, to yield a more nuanced understanding of the study quality [34]. Study quality was evaluated based on seven criteria, including selection bias, confounding bias, attrition/exclusion bias, detection bias for exposure, selective reporting bias and other bias (Text S1). (a) Selection bias occurs if selections of the exposed and non-exposed participants were comparable in terms of, for example, eligibility, inclusion and exclusion criteria, health status and period of recruitment. (b) Confounding bias pertains to residual confounding when key confounders and modifiers (including age, sex, education, income and comorbidities/family history of diseases) were not adjusted for in the analyses resulting in poor internal validity. (c) For cohort studies, substantial loss to follow-up can result in attrition bias. For cross-sectional studies, reasons for sample exclusion should be documented to avoid exclusion bias. (d) Ensuring the accuracy of the exposure measurements can help avoid detection bias for exposure characterization and resulting misclassification. (e) Assessing an outcome by using well-established methods is also beneficial to lowering the risk of detection bias. (f) Selective reporting bias may occur when there is direct evidence that the study's outcomes outlined in the protocol or abstract are not reported. (g) Lastly, bias may also occur if there are other potential threats to internal validity such as those related to statistical rigor [35]. Each assessment criteria was rated as "definitely low", "probably low", "probably high" or "definitely high" risk of bias. The results of the overall risk of bias assessment were presented in a table with symbols as indicated in the rating tool.

Results

Of the 5543 articles being exported from the systematic search (Fig. 1), 2058 and 3266 articles were excluded due to duplicates and upon primary screening based on title and abstract, resulting in 219 articles for full-text screening. One hundred fifty-six articles were further excluded upon assessments for eligibility, yielding a total of 63 studies (1.8%) for this review.

Of the 63 studies reviewed, 31 (49.2%) were of cross-sectional design, 28 (44.4%) of longitudinal design (cohort studies) and the remaining four (6.3%) comprised of both cross-sectional and longitudinal analyses. Recruited participants were aged ≥15 years in all studies.

Evidence from Studies with Cross-Sectional Design

Tables 1, 2 and 3 show the summary characteristics of the 35 studies of cross-sectional design. These were mostly conducted in multi-context settings, including in the USA (*n*=9) [39, 46, 48, 49, 53–55, 63, 71], China (*n*=6) [41, 43, 44, 50, 56, 57], Canada (*n*=4) [36, 60–62], the UK (*n*=3) [51, 52, 66], France (*n*=2) [59, 64], India (*n*=2) [45, 70]; and one each in South Africa [67], Ghana [38], Australia [65], Austria [40], Germany [42], South Korea [68], Hong Kong [69] and Spain [47]; and one included data from both Spain and Belgium [37]. All studies comprised both male and female participants, excepting one that included only female (*n*=1) [42]. With respect to study size, three studies recruited ≤1000 [40, 53, 67], two between 1001 and 2500 [43, 47], six between 2501 and 5000 [42, 45, 49, 51, 59, 71], six between 5001 and 10,000 [37, 38, 48, 64, 65, 70], ten between 10,001 and 100,000 [36, 41, 44, 50, 56, 57, 60, 62, 68, 69], while eight had more than 100,001 participants [39, 46, 52, 54, 55, 61, 63, 66].

Regarding the measurement of outcome variables, 18/35 studies used measured SBP and/or DBP [38, 41, 43–45, 47–50, 53, 59, 60, 62, 64, 66, 67, 69, 71], five employed self-reported doctor-diagnosed hypertension [36, 37, 42, 65, 68], and four defined

Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram

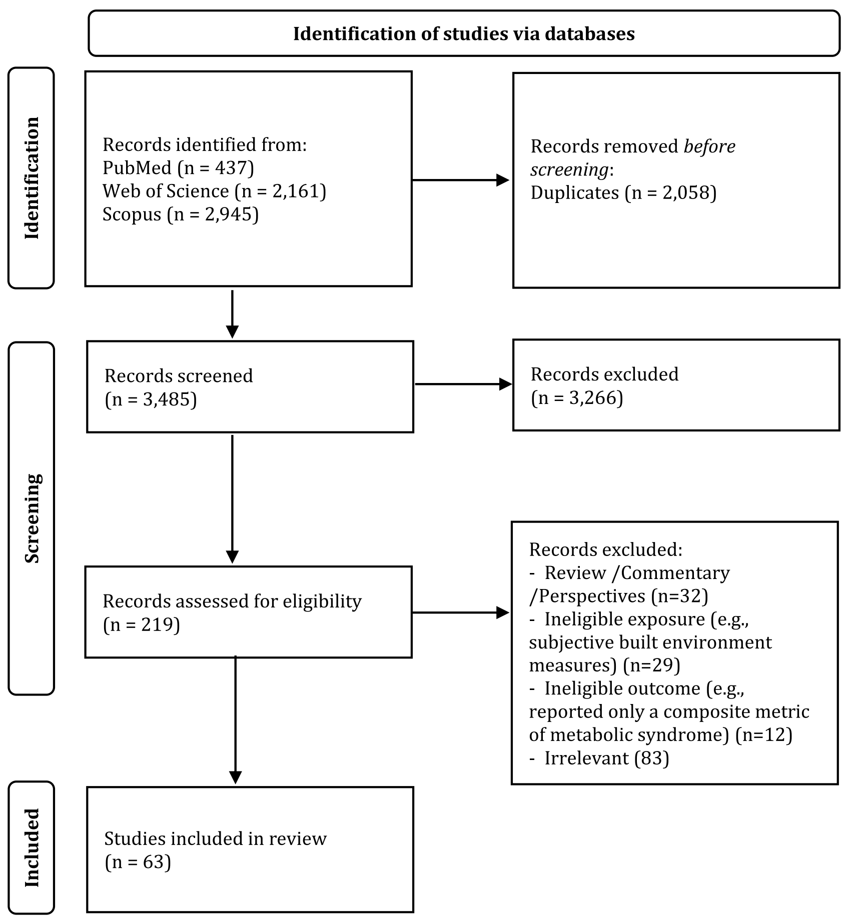

Table 1 Summary characteristics of cross-sectional studies on the associations between greenspace and cardiovascular risks and CVD endpoints

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Association between greenspace and blood pressure/hypertension							
Adhikari et al. (2021) [36]	British Columbia, Canada	22,418, 11,972	≥18	Both	Reported doctor-diagnosed high BP	Park availability, the number of parks within 1 km road network buffer around centroid of postal code	Lower odds of hypertension
Bauwelinck et al. (2020) [37]	Barcelona, Brussels	3400, 2335	≥18	Both	Self-reported hypertension	NDVI (100 m, 300 m, 500 m, circular), Landsat 8 (images during April–September)	N.S.
						Modified SAVI (within 100 m, 300 m, 500 m; circular buffer), Landsat 8 (images during April–September)	N.S.
						Distance to nearest greenspace	Longer distance to greenspace was associated with higher odds of hypertension in Barcelona
Boakye et al. (2023) [38]	Ghana	9,396	≥15	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg)	NDVI greenness (2 km; circular buffer), Landsat 7 (composites)	N.S.
						EVI (2 Km; circular buffer), MODIS (2015)	Lower odds of hypertension
Brown et al. (2016) [39]	Miami-Dade County, Florida	249,405	≥65	Both	Hypertension diagnosis (from Medicare beneficiaries)	NDVI (census block), ASTER satellite imagery of 2011)	Low- and medium-income neighbourhoods: lower risk of hypertension

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Dzhambov et al. (2018) [40]	Lower Inn Valley, Austria	555	≥18	Both	Measured SBP, DBP (two measurements) and self-reported hypertension (or anti-hypertensive medication use)	NDVI (100 m, 300 m, 500 m, 1000 m; circular buffer), Landsat 5 (on August 10, 1998)	Lower SBP for NDVI measured at 300 m, 500 m & 1000 m catchments
						SAVI (100 m, 300 m, 500 m, 1000 m; circular buffer), Landsat 5 (on August 10, 1998)	Lower SBP for SAVI measured at 300 m, 500 m & 1000 m
						Tree cover density (100 m, 300 m, 500 m, 1000 m; circular buffer), percentage of surface covered by woody vegetation >5 m calculated as the annual average value for the year 2000 based on a Landsat VCF map)	Lower SBP and DBP for tree cover measured at 100 m buffer
						Distance to forest area derived from CORINE 2000 land cover map	N.S.
						Distance to urban green space derived from OpenStreetMap data	N.S.

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
					Self-reported doctor-diagnosed hypertension	NDVI (100 m, 300 m, 500 m, 1000 m, circular buffer), Landsat 5 (on August 10, 1998)	Lower odds of hypertension for NDVI measured at 100 m, 300 m, 500 m & 1000 m buffers
						SAVI (100 m, 300 m, 500 m, 1000 m, circular buffer), Landsat 5 (on August 10, 1998)	Lower odds of hypertension for SAVI measured at 300 m & 500 m
						Tree cover density (100 m, 300 m, 500 m, 1000 m, circular buffer), percentage of surface covered by woody vegetation >5 m calculated as the annual average value for the year 2000 based on a Landsat VCF map	Lower odds of hypertension for tree cover measured at 300 m & 1000 m
						Distance to forest area present , CORINE 2000 land cover map	N.S.
						Distance to urban green space, OpenStreetMap data	N.S.

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
					Self-reported hypotension diagnosis	NDVI (100 m, 300 m, 500 m, 1000 m, circular buffer), Landsat 5 (on August 10, 1998)	Lower odds of hypotension for NDVI measured at 300 m, 500 m & 1000 m
						SAVI (100 m, 300 m, 500 m, 1000 m, circular buffer), Landsat 5 (on August 10, 1998)	Lower odds of hypotension for NDVI measured at 300 m
						Tree cover density (100 m, 300 m, 500 m, 1000 m, circular buffer), percentage of surface covered by woody vegetation >5 m calculated as the annual average value for the year 2000 based on a Landsat VCF map)	Lower odds of hypotension for NDVI measured at 300 m, 500 m & 1000 m
						Distance to forest area, CORINE 2000 land cover map	N.S.
						Distance to urban green space , OpenStreetMap data	N.S.
Huang et al. (2021) [41]	Guang-dong, Hubei, Jilin, Shandong, Shanxi, Shanghai, Yunnan, and Zhejiang, China	11,486	≥50	Both	Hypertension based on BP measures (≥140/90 mm Hg, three measurements) or self-reported medication use or treatment)	NDVI (1 Km, 500 m, 1.5 Km, 2 Km, 3Km circular buffers of neighbourhood centroid), Landsat 5 (nine images from May to Sep in 2007–2010)	Lower odds of hypertension with higher NDVI exposure reported in rural areas

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Jendrossek et al. (2017) [42]	Munich, Wesel	1753, 1310	Mean: 47.6, 45.7	F	Self-reported doctor-diagnosed hypertension	NDVI (500 m; circular buffer), Landsat 5 (average of exposure modelled based on address history over 15 years of follow-up, images from 2003 onwards)	N.S.
Jia et al. (2018) [43]	Longzihu, China	1944	≥40	Both	Hypertension based on BP measures (≥140/90 mm Hg) or self-reported doctor-diagnosis	NDVI modelled from MODIS (Jan to Dec, 2016)	Lower odds of hypertension reported among middle-aged and older adults
Jiang et al. (2021) [44]	Five counties, central China	39,094	≥18	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	NDVI and EVI (500 m; circular buffer), MODIS (3-year average values prior to the survey)	Lower DBP, SBP and lower odds of hypertension
Lane et al. (2017) [45]	Chennai, India	3150	>20	Both	Measured SBP, DBP (three measurements)	Inverse NDVI (250 m, 1,000 m; circular buffer), MODIS (Feb, Jun 2009)	Inverse NDVI associated with higher SBP, DBP
						Landsat-derived impervious surface area (250 m, 1000 m, circular buffer)	Higher impervious surface area was associated with higher SBP, DBP
Nguyen et al. (2021) [46]	San Francisco, USA	214,163	≥18	Both	Hypertension (electronic medical records)	Green streets (Google Street View)	Green streets associated with lower hypertension prevalence
Plans et al. (2019) [47]	Madrid, Spain	1625	40–75	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	Percentage of green land cover (300 m, 500 m, 1000 m, 1500 m; street network buffer), General Urban Plan data	Lower density of greenspaces within a 1500 m buffer was associated with an increased odds of hypertension in female
Poulsen et al. (2021) [48]	Pennsylvania, USA	9593	≥18	Both	Measured SBP, DBP (one measurement)	NDVI (1250 m; square buffer), MODIS	Lower DBP, SBP for Townships group

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Savin et al. (2021) [49]	Bronx, Chicago, Miami, and San Diego, US	3851	≥18	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	NDVI greenness (800 m; circular buffer), Landsat and Google Earth Engine (calculated from 2010 annual composite average)	N.S.
Yang et al. (2019) [50]	Liaoning, China	24,845	18–74	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	NDVI (500 m; circular buffer), Landsat 5 (two images from August 2010)	Lower SBP, lower odds of hypertension
						NDVI (1000 m, circular buffer), Landsat 5	Lower SBP, DBP and lower odds of hypertension
Association between greenspace and arterial stiffness							
de Keijzer et al. (2020) [51]	London, UK	4349	55–83	Both	Arterial stiffness measured by carotid-femoral pulse wave velocity	NDVI greenspace (500 m, 1000m; circular buffer), MODIS (images obtained between May and June of relevant years at baseline and the follow-up)	N.S.
						EVI greenspace (500 m, 1000m; circular buffer)	N.S.
						VCF greenspace (500 m, 1000 m; circular buffer), MODIS images of VCF were provided as annual values	N.S.
Lai et al. (2022) [52]	UK-wide, multiple cities	169,704	≥39	Both	Measured pulse wave arterial stiffness index	NDVI greenness (0.5 km; circular buffer), 0.50-m resolution multispectral colour infrared (CIR) data collected by Bluesky	Lower arterial stiffness index

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Riggs et al. (2021) [53]	Louisville, USA	73	23–84	Both	DBP, SBP, arterial stiffness measured by augmentation index	NDVI greenness (200 m, 1 Km; circular buffer), US Geological Survey	Lower augmentation index (for greenness measured at 200 m, 1 km) and lower SBP (for greenness measured at 200 m)
Association between greenspace and cardiovascular disease endpoints							
Brown et al. (2023) [54]	Miami-Dade County, FL, USA	249,405	≥65	Both	Ischemic stroke (433.01, 433.11, 433.21, 433.31, 433.81, 433.91, 434, 434.01, 434.1, 434.11, 434.9, 434.91), haemorrhagic stroke (430, 431), TIA (435, 435.1, 435.3, 435.8, 435.9), unknown stroke (436, 997.02)	NDVI greenness (census block), ASTER satellite imagery (2011)	Lower odds of TIA. N.S. for ischemic stroke, haemorrhagic stroke, and unknown stroke
Jia et al. (2018) [43]	Longzihu, China	1944	≥40	Both	CHD (defined as ≥1 major epicardial coronary artery with ≥50 stenosis of lumen) diagnosed based on coronary computed tomography with contrast or coronary angiography	NDVI modelled from MODIS (Jan to Dec, 2016)	Middle aged (40-59) and older (≥60) adults: lower odds of CHD
					Stroke (defined based on modified WHO definition of stroke) diagnosed based on computed tomography and/or Magnetic resonance imaging scan	NDVI modelled from MODIS (Jan to Dec, 2016)	Middle aged (40-59) and older (≥60) adults: lower odds of stroke
Wang et al. (2019) [55]	Miami-Dade County, Florida	249,405	≥65	Both	MI, IHD, HF, and atrial fibrillation as accessed from beneficiary summary file	NDVI greenness (census block), ASTER satellite imagery (2011)	Lower odds of IHD, HF and any heart disease. N.S. for MI and atrial fibrillation

Table 1 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Wang et al. (2022) [56]	Shenyang, Anshan and Jinzhou, China	24,799	≥18	Both	Self-reported doctor-diagnosed CVDs or stroke	Street view greenness (800 m; circular buffer), Tecent Map's street view images	Lower ORs for CVDs. N.S. for stroke
						Street view greenness-tree (800 m, circular buffer), Tecent Map's street view images	N.S. for CVDs and stroke.
						Street view greenness-grass (800 m, circular buffer), Tecent Map's street view images	Lower ORs for CVDs. N.S. for stroke
						NDVI greenness (800 m, 1000 m, 1500 m; circular buffer), Landsat 5	N.S. for CVDs and stroke.
Yang et al. (2020) [57]	Liaoning, China	24,845	≥18	Both	Self-reported physician-diagnosed CVD including MI, heart failure, CHD, cerebral thrombosis, cerebral haemorrhage, cerebral embolism, or subarachnoid haemorrhage	NDVI and SAVI (500 m, 1000 m; circular buffer), Landsat 5 (greenest month of 2010)	Lower odds of CVD with higher exposure to NDVI and SAVI at 500 m and 1000 m

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

**Buffer radii and type for definition of neighbourhood(s) are specified within brackets

ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; *BP*, blood pressure; *CHD*, coronary heart disease; *CVDs*, cardiovascular diseases; *DBP*, diastolic blood pressure; *EVI*, enhanced vegetation index; *F*, female; *HF*, heart failure; *ICD*, International Classification of Diseases; *IHD*, ischemic heart disease; *LAI*, leaf area index; *MAP*, mean arterial pressure; *M*, male; *MI*, myocardial infarction; *mm Hg*, millimeters of mercury; *MODIS*, Moderate Resolution Imaging Spectroradiometer; *NDVI*, normalized difference vegetation index; *N.S.*, not significant; *SAVI*, soil-adjusted vegetation index; *SBP*, systolic blood pressure; *TIA*, transient ischemic attack; *VCF*, vegetation continuous fields; *WHO*, World Health Organization

Table 2 Summary characteristics of cross-sectional studies on the associations between walkability and cardiovascular risks and CVD endpoints

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Association between walkability and blood pressure/hypertension							
Adhikari et al. (2021) [36]	British Columbia, Canada	22,418, 11,972	≥18	Both	Reported doctor-diagnosed high BP	Walkability index (1 km road network buffer around centroid of postal code) modelled from residential density, commercial floor-to-area ratio, land-use mix and interaction density	Lower odds of hypertension
Braun et al. (2016) [58] *(Health & Place)*	Forsyth County, New York, Baltimore, St. Paul, Chicago, Los Angeles, US	3227	53–94	Both	Measured SBP, DBP (three measurements) and hypertension (≥130/85 mm Hg, anti-hypertensive medication use)	Street Smart Walk score (higher values reflect greater walkability)	Lower DBP
de Courrèges et al. (2021) [59]	Lille, Dunkirk, France	3218	40–65	Both	Measured SBP (two measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	Neighbourhood walkability (500 m Euclidean and network buffers) modelled from residential density, street connectivity and land use diversity) and Walk score (1-mile radius)	Lower SBP, lower prevalence of hypertension
Howell et al. (2019) (*JAHA*) [60]	Ontario, Canada	44,448	40–74	Both	Measured SBP	Walkability (dissemination area), modelled from population density, dwelling density, street connectivity and number of accessible destinations	Lower walkability was associated with higher SBP
Howell et al. (2019) (*EI*) [61]	Ontario, Canada	2,496,458	40–74	Both	Hypertension as shown in hospital admission record or physician's validation	Walkability (800 m network buffer) constructed from population density, residential density, street connectivity, and number of retail or service destination	Lower walkability associated with higher odds of hypertension

Table 2 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Jia et al. (2018) [43]	Longzihu, China	1944	≥40	Both	Hypertension based on BP measures (≥140/90 mm Hg, anti-hypertensive medication use) or self-reported doctor-diagnosis	Walk score	Middle aged (40–59) adults: lower odds of hypertension
Loo et al. (2017) [62]	Toronto, Canada	78,023	≥18	Both	Measured SBP, DBP	Walk score measured from distance to amenities, population density, block length and intersection density	Lower DBP, SBP
Makram et al. (2023) [63]	Houston, US	1.1 million	≥18	Both	ICD-10 for hypertension (I10, I11.0, I11.9, I12.0, I12.9, I13.0, I13.10, I13.11, I13.2, I15.0, I15.1, I15.2, I15.8, I15.9)	Walkscore (zip code) modelled from amenities of education, retail, food, recreational and entertainment	Lower odds of hypertension
Méline et al. (2017) [64]	Paris, France	5993	38–84	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	Walk score (1-mile radius) measured from distance to facility categories of educational, retail, food, recreational and entertainment	Lower SBP, DBP
Müller-Riemenschneider et al. (2013) [65]	Perth, Australia	5970	>25	Both	Self-reported doctor-diagnosed hypertension	Walkability (800 m road network buffer) modelled from residential density, street connectivity and land use mix	N.S.
Sarkar et al. (2018) [66]	UK-wide, multiple cities	429,334	38-73	Both	Measured SBP, DBP (two measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	Walkability (1, 1.5 and 2 km street catchment) modelled from densities of housing density, retail outlets and public transport, street-level movement density and network distance to destinations	Lower DBP, SBP and lower odds of hypertension

Table 2 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Savin et al. (2021) [49]	Bronx, Chicago, Miami, and San Diego, USA	3851	≥18	Both	Measured SBP, DBP (three measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	Walkability (800 m circular buffer), modelled from density of intersections, retail spaces and residences	Lower SBP
Association between walkability and arterial stiffness							
Lai et al. (2022) [52]	UK-wide, multiple cities	169,704	≥39	Both	Measured pulse wave arterial stiffness index	Walkability (1 km street catchment) modelled from densities of housing density, retail outlets and public transport, street-level movement density and network distance to destinations	Lower arterial stiffness index
Association between walkability and cardiovascular disease endpoints							
Jia et al. (2018) [43]	Longzihu, China	1944	≥40	Both	CHD (defined as ≥1 major epicardial coronary artery with ≥50 stenosis of lumen) diagnosed based on coronary computed tomography with contrast or coronary angiography	Walk score	Middle aged (40-59) and older (≥60) adults: lower odds of CHD
					Stroke (defined based on modified WHO definition of stroke) diagnosed based on computed tomography and/or Magnetic resonance imaging scan	Walk score	N.S.

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

**Buffer radii and type/ definition of neighbourhood(s) are specified within brackets

ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; *BP*, blood pressure; *CHD*, coronary heart disease; *CVDs*, cardiovascular diseases; *DBP*, diastolic blood pressure; *EVI*, enhanced vegetation index; *F*, female; *HF*, heart failure; *ICD*, International Classification of Diseases; *IHD*, ischemic heart disease; *LAI*, leaf area index; *MAP*, mean arterial pressure; *M*, male; *MI*, myocardial infarction; *mm Hg*, millimeters of mercury; *MODIS*, Moderate Resolution Imaging Spectroradiometer; *NDVI*, normalized difference vegetation index; *N.S.*, not significant; *SAVI*, soil-adjusted vegetation index; *SBP*, systolic blood pressure; *TIA*, transient ischemic attack; *VCF*, vegetation continuous fields; *WHO*, World Health Organization

Table 3 Summary characteristics of cross-sectional studies on the associations between other attributes of built environment and cardiovascular risks

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
Association between other attributes of built environment and blood pressure/hypertension							
Malambo et al. (2018) [67]	Cape Town, South Africa	341	≥35	Both	Measured SBP, DBP (two measurements) and hypertension (≥140/90 mm Hg)	Road distance to community centre	Higher DBP with longer distance to community centre
						Road distance to shopping centre	Higher SBP with longer distance to shopping centre
Lee et al. (2021) [68]	Gyeonggi, South Korea	14,43	≥45	Both	Self-reported doctor-diagnosed hypertension	Density of physical activity facilities (546 administrative districts for all attributes)	N.S.
						Density of public parks	N.S.
						Density of fast-food restaurants	Higher density of fast-food restaurants was associated with lower odds of hypertension
						Proximity to public physical activity facilities	N.S.
						Proximity to public parks	N.S.
						Proximity to public transit	N.S.
						Street connectivity	N.S.
						Residential density	N.S.
						Commercial density	N.S.
						Industrial density	N.S.
						Land-use mix	N.S.
Sarkar et al. (2021) [69]	Hong Kong SAR	37,656	≥16	Both	Measured SBP, DBP, MAP (two measurements) and hypertension (≥140/90 mm Hg, anti-hypertension medication use)	Neighbourhood residential density (0.5 mile; 1 mile for sensitivity analysis)	Lower DBP, SBP, MAP and lower odds of hypertension
						Housing units per building block	Lower DBP, SBP, MAP and lower odds of hypertension
						Floor area, square feet	Lower DBP, SBP, MAP and lower odds of hypertension
Association between other attributes of built environment and arterial stiffness							
Corlin et al. (2018) [70]	Southern India	6166	20–75	Both	Mean carotid-femoral pulse wave velocity	Satellite derived land cover (crops, grass, shrubs or trees as rural; built-up areas as urban)	Residing in urban areas was associated with higher mean carotid femoral pulse wave velocity

Table 3 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Outcome(s)*	Exposure(s)**	Findings
						Distance to urban centre (interpreted as each 10 km increase in distance from the urban centre)	Increasing distance to urban centre was associated with lower mean carotid femoral pulse wave velocity

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

**Buffer radii and type/ definition of neighbourhood(s) are specified within brackets

ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; *BP*, blood pressure; *CHD*, coronary heart disease; *CVDs*, cardiovascular diseases; *DBP*, diastolic blood pressure; *EVI*, enhanced vegetation index; *F*, female; *HF*, heart failure; *ICD*, International Classification of Diseases; *IHD*, ischemic heart disease; *LAI*, leaf area index; *MAP*, mean arterial pressure; *M*, male; *MI*, myocardial infarction; *mm Hg*, millimeters of mercury; *MODIS*, Moderate Resolution Imaging Spectroradiometer; *NDVI*, normalized difference vegetation index; *N.S.*, not significant; *SAVI*, soil-adjusted vegetation index; *SBP*, systolic blood pressure; *TIA*, transient ischemic attack; *VCF*, vegetation continuous fields; *WHO*, World Health Organization

hypertension using either hospital record [46, 61, 63] or health insurance record [39]. One study included BP readings, self-reported doctor-diagnosed hypertension and self-reported hypotension as outcome variables [40]. Four studies measured arterial stiffness employing either carotid-femoral pulse wave velocity [51, 70] or augmentation index [53] or arterial stiffness index measured from pulse waveform [52]. Among the 19 studies that measured BP, hypertension was defined using cut-off points for SBP and DBP of ≥140/90 mm Hg (n=12) [38, 41, 43, 44, 47, 49, 50, 59, 64, 66, 67, 69] or ≥130/85 mm Hg (n=1) [71], while the remaining six did not define any cut-off point [40, 45, 48, 53, 60, 62]. Of the 19 studies employing measured SBP and/or DBP, BP measurements were repeated three times in nine studies [38, 41, 44, 45, 47, 49, 50, 64, 71], two times in six studies [40, 53, 59, 66, 67, 69], once in one study [48], while relevant information were not provided in the remaining three studies [43, 60, 62]. Of the 13 studies using BP cut-off points to define hypertension, 11 additionally employed antihypertensive medication intake as a criterion [41, 43, 44, 47, 49, 50, 59, 64, 66, 69, 71]. Five studies examined CVD events, which were assessed using either health insurance record [54, 55], imaging techniques [43] or self-reported questionnaire [56, 57]. Specific CVD events included composite CVD endpoints (n=3) [55–57], CHD (n=1) [43], stroke/ischemic stroke (n=3) [43, 54, 56], MI, IHD, heart failure and atrial fibrillation (n=1) [55].

A majority of the studies (n=33) employed geographic information system (GIS) to define participants' residential neighbourhood, one employed Google Street View data [46], and the remaining one employed both [56]. 17/34 studies employed straight-line (Euclidean) buffers to define residential neighbourhoods. The majority of studies used catchment radii of 500 m (n=10) [37, 40–42, 44, 50–52, 57, 59] and 1000 m (n=8) [40, 41, 45, 50, 51, 53, 56, 57]. A few studies employed street network buffers (n=8) of multiple catchment radii; namely, 800 m (n=3) [61, 65, 69], 1000 m (n=4) [36, 47, 52, 66] and 1600 m (n=3) [59, 65, 69]. One study employed 1250 m by 1250-m^2 buffers [48]. Five studies employed other predefined census geographies for exposure measurement including census block (n=3) [39, 54, 55], administrative district (n=1) [68] and dissemination area (n=1) [60]. Another five studies employed publicly available Walk score index which were linked to participants' postal codes [62], zip code [63] or residential addresses [43, 59, 71]. Relevant data were not found in one study [70].

Among the built environmental exposures, a majority of the studies measured residential greenness from multispectral remote sensing data, modelled in terms of metrics of normalized difference vegetation index (NDVI) (n=19) [37–45, 48–57], soil-adjusted vegetation index (SAVI) [37, 40, 57] or enhanced vegetation index (EVI) [38, 44, 51]. One study employed green land cover data (n=1) [47]. 17/19 studies measured NDVI greenness from satellite data including Landsat (n=9) [37, 38, 40–42, 49, 50, 56, 57], Moderate Resolution Imaging Spectroradiometer (MODIS) (n=6) [38, 43–45, 48, 51] and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (N=3) [39, 54, 55]. One study employed NDVI derived from 0.50-m spatial resolution colour infrared imagery [52]. Another study used data derived from the US Geological Survey [53]. Eight studies employed annual composite value to measure greenness exposure (n=8) [38, 39, 42–44, 49, 54, 55], while some selected greenness data from specific months of a year (n=8) [37, 40, 41, 45, 50–52, 57], or employed average greenness value over a 16-day period (n=1) [48]. The relevant information was not available in two studies [53, 56]. Of the studies employing data of multiple months selectively, seven selected only data from months during summer time [37, 40, 41, 50–52, 57], and one selected two images each from summer and winter time [45].

Walkability was the second most studied environment exposure (n=13). The majority of studies examining neighbourhood-level walkability developed overall metrics of walkability comprising multiple residential environmental attributes (n=7) [36, 49, 52, 60, 61, 65, 66] or employed a Walk score index (n=5) [43, 62–64, 71], and one study included both measures [59]. Walk score is a composite walkability index tagged to properties in USA and Canada and comprises distance to multiple amenities, block length and intersection density measured on either street network [43, 62, 71] or Euclidean buffers [63, 64] from each origin. Walk scores developed post-2010 such as Street Smart Walk score provides a more comprehensive measure of walkability using distance to amenities based on pedestrian-friendly street networks [72]. Other built-up environmental attributes included distance to greenspace/public parks (n=2) [37, 68], number of parks (n=1) [36], residential density (n=2) [68, 69], density of physical activity facilities (n=1) [68], impervious surface area (n=1) [45] and land cover type (n=1) [70].

Overall, the protective associations between exposure to greenness and hypertension or BP outcomes were evident in 12 out of 15 (80%) cross-sectional studies [36, 38–41, 43–48, 50], while three (20%) showed null results [37, 42, 49]. Eleven out of 12 (92%) cross-sectional studies reported that higher walkability was beneficially associated with hypertension or BP outcomes [36, 43, 49, 59–64, 66, 71], while one (8%) showed null results [65]. Evidence from two studies reported beneficial associations of walkability with arterial stiffness [52] and CHD [43]. Greenness exposure was also associated with lower arterial stiffness in two studies [52, 53], but another one showed insignificant results [51]. Greater greenness exposure was also found to protect against composite CVDs [55–57], CHD [43], transient ischemic attack [54], IHD and heart failure [55], but reported null results for MI and atrial fibrillation [55]. One study showed protective association of greenness with stroke [43], and two reported null results for stroke [56] and ischemic stroke [54]. Among the other attributes, longer street distance from home to the nearest community centre and proportion of impervious surface area were associated with higher blood pressure outcomes [45, 67]. Land-use mix (n=1) [68] within residential neighbourhood did not show statistically significant associations with hypertension. Longer distance to greenspace from home was found to be associated with a higher risk of hypertension [37], while one study reported null results [68]. One study found an inverse association between distance to urban centre and carotid-femoral pulse wave velocity [70]. One study showed beneficial association between residential density and hypertension [69], while one showed null results [68].

Evidence from Studies of Longitudinal Design

Tables 4, 5 and 6 show the summary characteristics of longitudinal studies. The 32 longitudinal studies were mostly conducted in Western settings, namely USA (n=10) [49, 58, 71, 75, 84–86, 95, 96, 99], Canada (n=5)

[82, 83, 88, 91, 94] and Australia (n=2) [77, 93], and one each in Belgium [73], Italy [87], Lithuania [74], Luxembourg [78], Spain [81], Thailand [76], Switzerland [90] and UK [51]. Others were conducted in Asia, including mainland China (n=3) [79, 80, 97], and one each in Hong Kong [69], India [98], South Korea [89] and Israel [92]. Three studies [85, 96, 99] involved only female participants, while two [84, 93] included only male participants. With respect to the number of participants, five studies had a sample size of ≤1000 [71, 73–75, 78], three had between 1001 and 2500 [58, 77, 94], two between 2501 and 5000 [49, 51], five between 5001 and 10,000 [79, 80, 93, 95, 98], seven between 10,001 and 100,000 [69, 76, 86, 92, 96, 97, 99] and ten included participants more than 100,001 [81–85, 87–91].

The outcome variables included measured hypertension and/or BP outcomes (n=13) [49, 58, 69, 71, 73–75, 77–80, 95, 98], self-reported hypertension (n=1) [76], hypertension derived from hospital admission and annual health examination records (n=1) [94], arterial stiffness (n=1) [51] and cardiovascular events derived from medical records (n=15) [81–93, 96, 97] or self-reported questionnaire (n=1) [99]. Specific CVD events included composite CVD endpoints [mortality: [82–84, 86, 87, 93, 96]; both hospitalization and mortality: [89]], IHD mortality [87, 90, 91], cerebrovascular mortality [87], hypertension-related mortality [90], CHD [mortality: [85, 99]; both hospitalization and mortality: [89, 99]], CHD or MI [99], MI [hospitalization: [82, 92]; both hospitalization and mortality: [89]], heart failure [82], total stroke [hospitalization: [87, 88, 92]; mortality: [85, 90, 91, 93]; both hospitalization and mortality: [89]], hemorrhagic stroke [both hospitalization and mortality: [89]] and ischemic stroke and/or transient ischemic attack [hospitalization: [81]; both hospitalization and mortality: [89, 97]]. The follow-up periods of the studies were 2.2–40 years, 4 years and 2–27 years for hypertension, arterial stiffness and cardiovascular events respectively. The outcome variables were measured at multiple time points (i.e. at each follow-up) in 9 of 13 longitudinal studies for hypertension [49, 58, 69, 71, 77–80, 95], and one study for arterial stiffness [51]. Among the 13 studies that measured BP, cut-off points for SBP and DBP of either ≥140/90 mm Hg [49, 69, 74, 79, 80, 95] or ≥130/85 mm Hg [71, 77] were employed, one study measured ambulatory BP during day and night time [73], while four did not define any cut-off point [58, 75, 78, 98]. Of the 13 studies that measured SBP and/or DBP, BP measurements were repeated three times in seven studies [49, 58, 71, 75, 78, 80, 98] and two times in four studies [69, 74, 79, 95]. The outcomes were measured every 15 min or 30 min during day and night time, respectively in one study [73], and the remaining one did not specifically mention about repeated measurements [77]. Seven studies additionally employed antihypertensive medication as a criteria to define hypertension [49, 69, 71, 74, 77, 80, 95].

All the longitudinal studies employed GIS to define residential neighbourhoods. The majority of studies employed straight-line residential catchments (n=17), mostly of buffer radius 500 m (n=10) [51, 73, 79, 81, 83, 86, 90, 91, 93, 98], 1000 m (n=5) [51, 73, 86, 87, 96], 300 m (n=5) [73, 81, 87, 93, 98] and 250 m (n=5) [82, 83, 85, 86, 88]. Only four studies employed street network catchment of buffer sizes 500 m [78], 800 m [69, 78] and 1000 m [75, 77, 78]. Two studies assigned a 250-m^2 pixel [84] and a 30-m pixel [92] containing participants' home address. Four studies employed a publicly available Walk score index linked to individual health data via postal codes [94] or residential locations [71, 95, 97]. Four studies employed other predefined census geographies for exposure measurement including city [80], sub-district [76], administrative district [89] and metropolitan statistical area [99]. Two studies measured distance to multiple attributes of built environment [74, 75].

Among the urban environmental exposures, a majority of the studies examined the associations with residential greenness in terms of NDVI (n=17) [51, 76, 77, 79–88, 90–93], EVI [51, 76, 79] or SAVI [78]. Other measures of greenness and urban land use included greenspace coverage [73, 75, 89, 90], greenspace count [75], distance to greenspace [74, 75], density of wooded environment [78] and satellite-derived built-up land-use [98]. Several studies examined associations of CVD risks and events with neighbourhood-level walkability (n=8) [49, 58, 71, 77, 94–97]. Besides greenness and walkability, one study additionally measured food environment and count, median size and type of public open spaces [77]. Multi-scalar residential density expressed in terms of floor area of the apartment, building block density and neighbourhood level density was measured in one study [69]. One measured distance to major road [74] and another one measured compactness modelled

Table 4 Summary characteristics of longitudinal cohort studies on the associations between greenspace and cardiovascular risks and CVD endpoints

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Association between greenspace and blood pressure/hypertension									
Bijnens et al. (2017) [73]	East-Flanders, Belgium	278	18–25	Both	12–19	Measured ambulatory BP (night-time measurement: 12:00–6:00; daytime measurement: 10:00–20:00)	(1) No (2) No (3) Yes (addresses at birth and at adult age)	Greenness (5000 m; sensitivity tests for 4000 m, 3000 m, 2000 m, 1000 m, 500 m, 300 m, 100 m, circular buffers), CORINE Land Cover 2000	Lower BP
Brazienė et al. (2018) [74]	Kaunas city, Lithuania	739	35–64	Both	6–15	Measured SBP, DBP, and arterial hypertension (≥140/90 mm Hg, anti-hypertensive medication use). Two BP measurements, two waves: 1992–2002, 2006–2008	(1) No (2) No (3) No (exclusion of movers)	Straight line distance to nearest green space extracted from spatial land cover datasets	Greater distance from greenspaces was associated with higher risk of arterial hypertension

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Jimenez et al. (2020) [75]	Twelve cities in US	517	Adults (mean: 4.4)	Both	40	Measured SBP, DBP in adulthood (three measurements, and BP calculated from average of 2nd & 3rd readings)	(1) Yes (2) Yes (all time points) (3) Yes	Distance (miles) to the closest green space (road network buffer)	Greater residential distance to green space at birth was associated with increased SBP and DBP in adulthood
								Average area (hectares) of green space within the neighbourhood (1 mile, road network buffer)	N.S. for SBP and DBP
								Green space count (1 mile, road network buffer)	One more greenspace within neighbourhood at birth was associated with decreased DBP. N.S. for SBP in adulthood
Paoin et al. (2023) [76]	Thailand	52,308	15–87	Both	8	Self-reported hypertension	(1) Yes (annual) (2) Yes (annual) (3) No (exclusion of movers)	NDVI and EVI greenness (sub-district), MODIS	Higher greenness exposure was associated with lower HRs of hypertension

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Paquet et al. (2014) [77]	Adelaide, South Australia	1419	≥18	Both	3.5	Measured SBP, DBP, and hypertension (≥130/85 mm Hg, anti-hypertension medication use). Two waves: 2000–2003, 2005–2006	(1) No (2) No (baseline only) (3) No	Public open space (NDVI, 1 Km, road network buffer), Landsat	N.S.
Tharrey et al. (2023) [78]	Luxembourg	395	≥18	Both	9	Measured SBP (three measurements, two waves: 2007–2009, 2016–2017)	(1) Yes (2009, 2018) (2) Yes (both waves) (3) NA	SAVI (500 m, 800 m, 1000 m, road network buffer), Landsat 7 and Landsat 8	N.S.
								Density of wooded environment (TCD) (500 m, 800 m, 1000 m, road network buffer), Copernicus Land Monitoring Service	N.S.

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Wensu et al. (2022) [79]	23 areas in China	5253	>80	Both	(2011–2018)	Measured SBP, DBP and hypertension (≥140/90 mm Hg). Two BP measurements, four waves: 2008, 2011, 2014, 2018.	(1) Yes (multiple time windows); (2) Yes (3) Yes (exclusion of movers as sensitivity test)	NDVI and EVI greenness (500 m, circular buffer), MODIS	Higher greenness exposure was associated with lower HRs of hypertension only in the high exposure group *(0.30 for NDVI and 0.21 for EVI)*
Yang et al. (2022) *(Environ. Research)* [80]	28 provinces in China	9649	≥45	Both	4	Measured SBP, DBP and hypertension (≥140/90 mm Hg, anti-hypertension medication use. Three measurements, three waves: 2011, 2013, 2015	(1) Yes (2010–2015) (2) Yes (all time points) (3) NA	NDVI greenness (city-level) Resource and Environment Science and Data Center (1 km)	Higher greenness exposure was associated with lower SBP, DBP and odds of hypertension
Association between greenspace and arterial stiffness									
de Keijzer et al. (2020) [51]	London, UK	4349	55–83	Both	4	Arterial stiffness measured by carotid-femoral pulse wave velocity (two measurements, 2007–2009, 2012–2013)	(1) Yes (two time points) (2) Yes (two time points) (3) Yes (address available for each follow-up)	NDVI, EVI and VCF greenspace (500 m, 1000 m, circular buffer), MODIS	N.S.

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Association between greenspace and cardiovascular events and mortality									
Avellaneda-Gómez et al. (2022) [81]	Catalonia, Spain	3,521,274	≥18	Both	2	Hospitalization from ischemic stroke or TIA (ICD-9: 433.x1, 434.x, 435.x and 436.5)	(1) No (2016-17) (2) No (3) No (baseline only)	NDVI greenness (300m, 500 m, circular buffer), Landsat 8 [May 1st, 2016; April 11th, 2017; April 18th, 2017; 12th June 2017; and 14th June 2017)	Higher greenness exposure was associated with lower HR of ischemic stroke or TIA hospitalizations
Chen et al. (2020) [82]	Ontario, Canada	1.4 million	35–100	Both	14	Incident MI (ICD-9: 410 and ICD-10: I21–22) and HF (ICD-9: 428 and ICD-10 I50); cardiovascular mortality (ICD-9: 401–459 and ICD-10: I10–I99)	(1) Yes (annual average) (2) Yes (yearly) (3) Yes (yearly postal codes available)	NDVI greenness (250 m, circular buffer), Landsat 5	Higher greenness exposure was associated with lower risks of incident MI and HF, and cardiovascular mortality
Crouse et al. (2017) [83]	Canada	1.3 million	≥19	Both	11	Cardiovascular mortality (ICD-10: I10–I69)	(1) Yes (annual maximum) (2) Yes (yearly) (3) Yes (yearly postal-code)	NDVI greenness (250 m and 500 m, circular buffer), MODIS	Higher greenness exposure was associated with lower HR in cardiovascular mortality

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Iyer et al. (2020) [84]	Pennsy-lvania, USA	128,568	Median: 66	M	8	Cardiovascular mortality (ICD-9: 390–459 and ICD-10: I00–I99)	(1) Yes (cumulative average) (2) Yes (yearly) (3) No (no mobility data)	NDVI greenness (250 m^2 pixel), MODIS data	Higher greenness exposure was associated with lower HR of cardiovascular mortality
James et al. (2016) [85]	USA	108,630	Mean: 68.98	F	8	CHD mortality (ICD-9: 390–429, 440–459); Stroke mortality (ICD-9: 430–438)	(1) Yes (exposure value updated as it changed over time) (2) Yes (3) Yes (biennial address updates)	NDVI greenness (250 m, circular buffer), MODIS	N.S.
Liao et al. (2022) [86]	Northern California, USA	83,560	≥18	Both	5.1	Cardiovascular mortality (ICD-10: I10.x-I70.x)	(1) Yes (yearly average); (2) Yes (yearly average); (3) No (baseline only)	NDVI greenness (250 m, 500 m, 1 Km, circular buffer), Landsat 8 (May to September)	Higher greenness exposure was associated with lower HR of cardiovascular mortality

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Orioli et al. (2019) [87]	Rome, Italy	1.26 million	≥30	Both	12	Cardiovascular mortality (ICD-9: 390–459); IHD mortality (ICD-9: 410–414); Cerebrovascular disease mortality (ICD-9: 431–436); Stroke incidence (ICD-9: 431, 433.x1, 434, 436)	(1) No (acquired on 17 July 2015) (2) No (baseline only) (3) No (baseline only)	NDVI and LAI (300 m, 1000 m, circular buffer), Landsat 8	Higher greenness exposure was associated with lower HR of mortality from CVD, IHD and cerebrovascular disease, and stroke incidence.
Paul et al. (2020) [88]	Ontario, Canada	4.25 million	35–85	Both	(2001–2013)	Stroke hospitalization [ischemic stroke hospitalization: ICD-9: 434, 436 or ICD-10: I63 (excluding I63.6), I64, H34.1; haemorrhagic stroke: ICD-9: 430, 431 or ICD-10: I60, I61]	(1) Yes (annual) (2) Yes (annual) (3) Yes (annual postal code)	NDVI greenness (250 m, circular buffer), Landsat 5	Higher greenness exposure was associated with lower HR of stroke hospitalization

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Seo et al. (2019) [89]	Seven metropolitan cities in Korea	351,409	≥20	Both	8	CHD (ICD-10, I20–I25); MI (ICD-10, I21–I24); total stroke (ICD-10, I60–69); haemorrhagic stroke (ICD-10, I60–I62); ischemic stroke (ICD-10, I63) *Note. (events included both hospitalization and mortality)*	(1) No (2005 data) (2) No (2005 data) (3) NA	Urban greenspace coverage (administrative districts), Ministry of Land, Infrastructure and Transport (Korea)	Higher greenness exposure was associated with lower HRs of CHD, MI, total stroke and ischemic stroke. N.S. for haemorrhagic stroke

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Vienneau et al. (2017) [90]	Switzerland	4,284,680	≥30	Both	7.8	CVD mortality (ICD-10: I00–I99); IHD mortality (ICD-10: I20–I25); stroke mortality (ICD-10: I60–I64); hypertension-related mortality (ICD-10: I10–I15)	(1) No (2) No (3) NA	NDVI greenness (150 m, 500 m, circular buffer), Landsat 8 (2014)	Higher NDVI greenness was associated with lower HRs of mortality from CVD, IHD, stroke and hypertension-related diseases for 150 m and 500 m
								Land use mapping of green spaces (150 m, 500 m, circular buffer), Swiss topographic landscape model (1-m accuracy; 2009–2015)	Higher green exposure was associated with lower HR of CVD mortality. N.S. for mortality from IHD, stroke and hypertension-related diseases
Villeneuve et al. (2012) [91]	Ontario, Canada	574,840	≥35	Both	22	CVD mortality (ICD-9: 400–440; ICD-10: I10–I70), IHD mortality (ICD-9: 410–414; ICD-10: I20–I25) and stroke mortality (ICD-9: 430–438; ICD-10: I60–I69)	(1) Yes (1989–1997); (2) Yes; (3) No (baseline only)	NDVI greenness (500 m buffer, circular buffer), Landsat Thematic Mapper data (30 m grid)	Higher NDVI greenness was associated with lower risk of deaths caused by CVD, IHD and stroke

Table 4 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Yitshak-Sade et al. (2017) [92]	Negev, Southern-Israel	23,110	≥18	Both	(2003-12)	Stroke (ICD-9: 432–435) and MI (ICD9: 410)	(1) Yes (2013–2015) (2) Yes (2013–2015) (3) No	NDVI greenness (30 m pixel), Landsat 8	Higher NDVI greenness was associated with lower odds of MI. N.S. for stroke.
Zijlema et al. (2019) [93]	Perth, Australia	9218	≥65	M	20	Cardiovascular mortality (ICD-9: 390–429, 440–448; ICD-10: I00–I59, I70–I78); Stroke mortality (ICD-9: 430–438; ICD-10: I60–I69)	(1) Yes (2) Yes (3) No (exclusion of movers)	NDVI greenness (100 m, 300 m, 500 m, circular buffer), Landsat 7 (June–October)	N.S.

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

**Buffer radii and type/ definition of neighbourhood(s) are specified within brackets

ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; *BP*, blood pressure; *CHD*, coronary heart disease; *CVDs*, cardiovascular diseases; *DBP*, diastolic blood pressure; *EVI*, enhanced vegetation index; *F*, female; *HF*, heart failure; *ICD*, International Classification of Diseases; *IHD*, ischemic heart disease; *LAI*, leaf area index; *MAP*, mean arterial pressure; *M*, male; *MI*, myocardial infarction; *mm Hg*, millimeters of mercury; *MODIS*, Moderate Resolution Imaging Spectroradiometer; *NDVI*, normalized difference vegetation index; *N.S.*, not significant; *SAVI*, soil-adjusted vegetation index; *SBP*, systolic blood pressure; *TIA*, transient ischemic attack; *VCF*, vegetation continuous fields; *WHO*, World Health Organization

Table 5 Summary characteristics of longitudinal cohort studies on the associations between walkability and cardiovascular risks and CVD endpoints

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Association between walkability and blood pressure/hypertension									
Braun et al. (2016) *(J Transp Health)* [58]	Birmingham, Chicago, Minneapolis, and Oakland, USA	1079	32–46	Both	6	Measured SBP (three measurements, two waves: 2000–2001, 2005–2006)	(1) Yes (2) Yes (2 time points) (3) Yes (included movers only)	Walkability index (3 km; circular buffer) modelled from population density, street connectivity, and food and physical activity resources	Walkability increment from residential relocation was associated with lower SBP
Braun et al. (2016) *(Health & Place)* [71]	Forsyth County, New York, Baltimore, St. Paul, Chicago, Los Angeles, USA	583	53–94	Both	5 to 8	Measured SBP, DBP (three measurements, two waves: 2004–2005, 2010–2012)	(1) No (data from May 2012 were used for both exams) (2) Yes (two time points) (3) Yes (included movers only)	Street Smart Walk score (calculated based on street distance to different types of amenities)	Walkability increment from residential relocation was associated with higher SBP
Chiu et al. (2016) [94]	Ontario, Canada	2114	≥20	Both	4.3	Incident hypertension (hospital admission; annual health examinations for controls)	(1) Yes (as of 2012) (2) Yes (3) Yes (included movers only)	Walk Score (postcode) calculated for participants moving addresses	Moving from low walkability neighbour-hood to high walkability neighbour-hood was associated with lower risk of incident hypertension

Table 5 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Jones et al. (2021) [95]	South-eastern USA	6894	≥45	Both	27	Incident hypertension (≥140/90 mm Hg, anti-hypertensive medication use). Two BP measurements, two visits: 2003–2007, 2013–2017	(1) No (2) No (baseline only) (3) No	Street Smart Walk score (calculated based on street distance to different types of amenities)	Lower odds of hypertension
Paquet et al. (2014) [77]	Adelaide, South Australia	1419	≥18	Both	3.5	Measured SBP, DBP and hypertension (≥130/85 mm Hg, anti-hypertensive medication use). Two waves: 2000–2003, 2005–2006	(1) No (2) No (baseline only) (3) No	Walkability index (1 Km; street network buffer) modelled from dwelling density, interaction density, land use entropy and retail footprint	N.S.
Savin et al. (2021) [49]	Bronx, Chicago, Miami, and San Diego, USA	2860	≥18	Both	6	Measured SBP, DBP, hypertension (≥140/90 mm Hg, anti-hypertensive medication use). Three BP measurements, two visits: 2008–2011, 2014–2017	(1) No (2) No (baseline only) (3) No (excluded movers)	Walkability (800 m; circular buffer) modelled from density of intersections, retail spaces and residences	N.S.

Table 5 (continued)

Authoring team, year	Setting	Sample size	Age (years)	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Association between walkability and cardiovascular diseases									
India-Aldana et al. (2021) [96]	New York City	13,832	34–65	F	27	Cardiovascular mortality	(1) No (single time point) (2) No (baseline only) (3) No (sensitivity for non-movers only)	Walkability (1 Km; radial buffer) modelled from residential density, destination accessibility, intersection density, and density of public transit	N.S.
Yang et al. (2022) *(Environ. Pollution)* [97]	Zhejiang, China	27,375	≥40	Both	4.08	Ischemic stroke (ICD-10: I63, I69.3) *Note. either the first nonfatal ischemic stroke event or ischemic stroke death without a history of ischemic stroke*	(1) No (2) No (3) No (baseline only)	Walk Score modelled from intersection density, residential density, access to public transit and sidewalk availability	Higher walk score was associated with lower HR of ischemic stroke event

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

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Table 6 Summary characteristics of longitudinal cohort studies on the associations between other attributes of built environment and cardiovascular risks and CVD endpoints

Authoring team, year	Setting	Sample size	Age	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Association between other attributes of built environment and blood pressure/hypertension									
Brazienė et al. (2018) [74]	Kaunas city, Lithuania	739	35–64	Both	6–15	Measured SBP, DBP (two measurements), and arterial hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	(1) No (2) No (3) No (exclusion of movers)	Straight line distance to major road extracted from spatial land cover datasets	Shorter distance to major road was associated with higher risk of arterial hypertension
Milà et al. (2020) [98]	Hyderabad, India	6039	>18	Both	14	Measured SBP, DBP (three measurements)	(1) Yes (14-y change) (2) Yes (3) No	Increase in built-up land use (300 m & 500 m, circular buffer) from Landsat 5 and 7 data over 1995–2009	Increment in built-up land use was associated with higher SBP and DBP
Paquet et al. (2014) [77]	Adelaide, South Australia	1419	≥18	Both	3.5	Measured SBP, DBP and hypertension (≥130/85 mm Hg, anti-hypertensive medication use). Two waves: 2000–2003, 2005–2006)	(1) No (2) No (baseline only) (3) No	Relative food environment index (1 km, road network buffer; the ratio of fast-food restaurants and unhealthy food stores to healthful food stores)	N.S.
								Public open space (number; 1 km, road network buffer)	N.S.
								Public open space (median size; 1 km, road network buffer)	N.S.
								Public open space (type; 1 Km, road network buffer)	N.S.

Table 6 (continued)

Authoring team, year	Setting	Sample size	Age	Sex	Follow-up (years)	Outcome(s)*	(1) Changes of BE data (2) Longitudinal exposure measure (3) Mobility data on changes in residential address	Exposure(s)**	Findings
Sarkar et al. (2021) [69]	Hong Kong SAR	25,209	≥16	Both	2.2	Measured SBP, DBP, MAP (two measurements) and hypertension (≥140/90 mm Hg, anti-hypertensive medication use)	(1) (1) (1) Yes (2) Yes (3) Yes	Neighbourhood residential density (0.5 mile; 1 mile for sensitivity analysis)	N.S.
								Housing units per building block	Lower DBP, SBP, MAP and N.S. for hypertension
								Floor area, square feet	Lower DBP, SBP, MAP and lower odds of hypertension
Griffin et al. (2013) [99]	76 sites in the USA	45,376	50–79	F	7.5	CHD death, CHD death or first MI, first CHD event [CHD death, MI, confirmed angina, and coronary revascularization] (derived from survey-based questionnaire and/or death record)	(1) No (baseline only) (2) No (baseline only) (3) No (baseline only)	Overall compactness (metropolitan statistical area) modelled from residential density, mixed land use, street connectivity and centredness	Increment in compactness was associated with lower HRs of CHD event, and CHD death or first MI
								Street connectivity	N.S.
								Centredness	N.S.
								Mixed land use	Higher mixed land use exposure was associated with lower HR of CHD death or first MI
								Residential density	Higher residential density exposure was associated with lower HRs of CHD event, and CHD death or first MI

Table 6 (continued)

Notes:

*Numbers of repeated measurements for blood pressure are specified within brackets

**Buffer radii and type/ definition of neighbourhood(s) are specified within brackets

ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; *BP*, blood pressure; *CHD*, coronary heart disease; *CVDs*, cardiovascular diseases; *DBP*, diastolic blood pressure; *EVI*, enhanced vegetation index; *F*, female; *HF*, heart failure; *ICD*, International Classification of Diseases; *IHD*, ischemic heart disease; *LAI*, leaf area index; *MAP*, mean arterial pressure; *M*, male; *MI*, myocardial infarction; *mm Hg*, millimeters of mercury; *MODIS*, Moderate Resolution Imaging Spectroradiometer; *NDVI*, normalized difference vegetation index; *N.S.*, not significant; *SAVI*, soil-adjusted vegetation index; *SBP*, systolic blood pressure; *TIA*, transient ischemic attack; *VCF*, vegetation continuous fields; *WHO*, World Health Organization

from street connectivity, mixed land use, centredness and residential density [99]. All the 17 studies measuring greenness employed satellite data of moderate to low spatial resolution; 10 used Landsat data [77, 81, 82, 86–88, 90–93], six used MODIS [51, 76, 79, 83–85] and one derived data from other resource [80]. Eleven of the 17 studies employed annual composite value to measure greenness exposure [51, 76, 79, 80, 82–86, 88, 91], three selected greenness data from specific years over the follow-up period [90, 92, 93], and three measured the exposure at baseline only [77, 81, 87]. Of the 17 studies, eight selected only data from months in summer time [51, 77, 81, 83, 86, 87, 90, 93], one employed monthly data [80], two derived data of representative months to develop a seasonally-time varying measure for every year [84, 85], and six did not report information with regard to the months of the year in which greenness was assessed [76, 79, 82, 88, 91, 92]. For studies examining neighbourhood-level walkability, the majority developed overall metrics of walkability comprising multiple component built environment attributes measured from participants' residential locations (n=4) [49, 58, 77, 96] or employed Walk score (n=4) [71, 94, 95, 97]. Three of the eight studies on walkability employed quasi-experimental design examining the effect of moving addresses from low to high walkable neighbourhoods on hypertension [94] and BP reductions [58, 71].

With respect to the temporal frequency of exposure assessment, nine of the 25 studies examining the associations with greenness and walkability measured the exposure at a single time point [49, 77, 81, 87, 90, 92, 95–97], and 16 at multiple time points [51, 58, 71, 76, 78–80, 82–86, 88, 91, 93, 94]. Of the nine studies employing a single-time exposure measurement, two restricted analyses to only non-movers [49, 96]. Of the 16 studies measuring the exposure at multiple time points, time-varying data were employed in 15 studies, and one employed data of a single time point [71]. The exposure value was assigned for each address at each follow-up in five studies [51, 82, 83, 85, 88], three included only participants who moved residence [58, 71, 94], three included non-movers only [76, 79, 93], and mobility data was not available in another five studies [78, 84, 86, 91, 92]. Among the studies examining other attributes of urban environment, three measured built environment (including distance to major road, food environment, public open space and compactness) at a single time point

[74, 77, 99], another employed yearly Landsat data to measure land use change over time [98], while another examined associations of multi-level density on hypertension across two waves of the cohort [69].

Six out of eight longitudinal studies (75%) showed protective associations of higher exposure to greenness with hypertension or BP [73–76, 79, 80], while two showed null results [77, 78]. Of the eight longitudinal studies examining links between greenness and cardiovascular mortality, a protective association was observed in seven (88%) studies [82–84, 86, 87, 90, 100], while one reported null results [93]. Five studies reported association between greenness and total stroke hospitalization/mortality [87–91], while three reported null results [85, 92, 93]. The protective associations of greenness with MI [82, 89, 92], ischemic stroke and/or transient ischemic attack [81, 89, 97] and heart failure[82] were evident. The analysis by CVD mortality/event sub-types also showed protective associations of greenness with IHD mortality [87, 90, 91], cerebrovascular mortality [87] and hypertension-related mortality [90]. One study showed protective association between greenness and CHD [89], while one showed null findings [85]. Evidence from two studies also showed null associations of greenness with hemorrhagic stroke [89] and arterial stiffness [51].

Three out of six longitudinal studies (50%) reported that residing in neighbourhoods with higher walkability was beneficially associated with hypertension or BP outcomes [58, 94, 95]. Three of these studies employed a quasi-experimental design following-up participants who moved residential address by measuring walkability before and after the move and reported protective association of increase in walkability with BP outcomes [58, 94], but one study found counterintuitive results [71]. One study found null associations between walkability and cardiovascular mortality [96], whereas one reported reduced risk of ischemic stroke event with higher walkability [97]. Among the other attributes of urban environments, one study reported beneficial associations of compactness with CHD mortality and incident MI [99]. Another study showed non-beneficial association between built-up land use and BP outcomes [98], and one did not find statistically significant associations of food environment index with BP outcomes [77]. Another study reported protective association of residential floor area with hypertension and BP outcomes, while a positive association was reported with building block density. Participants moving to residences of lower floor area had a higher odds of hypertension in reference to those who did not move [69].

Study Quality

Risk of biases pertaining to selection, selective reporting and other bias were rated as "probably low" in the 63 studies reviewed (Table S1). Forty-two out of 63 studies (67%) were rated as "probably high" risk of confounding bias because of being unable to account for basic socioeconomic status (i.e. age, sex, education and income) and/or comorbidities/family history of diseases in their statistical models. All but one of the studies explicitly specified about reasonable inclusion and exclusion criteria for participant recruitment and/or analysis (62/63, 98%). The remaining one study excluded participants under the age of 40 which accounted for 34% of the original dataset [43] and was considered to have "probably high" risk of exclusion bias. Twenty-nine out of 63 studies (46%) were rated as "probably high" risk of detection bias for exposure due to using only baseline exposure in longitudinal studies [49, 77, 87, 95–97] and/or modelling exposures based on geocodes of pre-defined administrative units [38, 39, 41, 47, 50, 51, 54–57, 60–63, 68, 76, 79, 80, 82, 83, 89, 91, 99]. Nine studies (14%) were rated as "probably high" risk of bias for outcome ascertainment owing to using self-reported data to identify hypertensive patients [36, 37, 42, 65, 68, 76] and CVDs [56, 57, 99]. Detailed profiles of each study included in this review have been summarized in Tables S2–S64.

Discussion

The review summarizes current evidence examining associations of urban built environment with cardiovascular risks and events. Overall, we report moderately-consistent evidence of associations of greenness with cardiovascular risks and major CVD events (cross-sectional studies: 12 of 15 on hypertension/BP and 2 of 3 on arterial stiffness; and among longitudinal studies: 6 of 8 on hypertension/BP, 7 of 8 on CVD mortality, 3 of 3 on IHD mortality and 5 of 8 on stroke hospitalization or mortality reporting inverse associations). A moderately-consistent protective association was also reported for walkability (cross-sectional studies: 11 of 12 on hypertension/BP and 1 of 1 on arterial stiffness; and in longitudinal studies: 3 of 6 on hypertension/BP and 1 of 2 studies on CVD events being protective).

Study design is an important criterion for determining the validity of evidence. In this review, 49% of the studies examining the association between urban environment and cardiovascular health employed cross-sectional design. Cross-sectional study design is prone to bias associated with common method variance emerging from the use of data measured at a single time point [101], implying that causal inference cannot be established. Additionally, the majority of studies were conducted in Western settings (76%), while studies from Asia accounted for 24% of the remainder. Future studies should rely on longitudinal data, with the assessment of cardiovascular health and measurements of exposures conducted at multiple time points to enable a better understanding of the potential causal relationships between urban environment and CVD risks. Quasi-experimental study design or natural urban experiments, appropriately supported by advanced modelling techniques (such as propensity score matching and inverse probability weighting) may also be leveraged to support causal explanation of associations of built environment interventions on CVD risks; such as the health effects of moving from one neighbourhood setting to another. There is a need to collect evidence from varied geographical contexts for greater external validity.

Rigorous health outcome assessment is fundamental to conducting robust health-related research. Ten percent of the studies relied on questionnaire-based methods to identify participants' hypertension status. This may be prone to a degree of subjectivity associated with recall bias, thereby affecting the validity of outcome assessment. Commonly used valid diagnostic methods in clinical settings include measuring health parameters (such as BP using electronic monitors) by trained interviewers or nurses or obtaining data directly from health registries and hospital records (enabling data analyses at multiple time points). The use of data from health insurance agencies has also become more common, as in one of the reviewed studies from Florida using annual claims of chronic conditions for all beneficiaries [39]. Besides the use of circulatory markers of CVD risks (like BP) which are transient in nature and thus prone to diurnal fluctuations based on surrounding environment and activities, more stable markers such as arterial stiffness and other CVD biomarkers may produce robust results.

Accurate definition of functional activity neighbourhood for measuring built environment is an important factor determining reliability of the reported results. In the present review, neighbourhoods were defined in terms of buffers of different shapes (primarily Euclidean buffers and some employing street network buffers) and of different spatial scales (buffer radii), which may have contributed to some of the inconsistencies in the reported findings. Street network buffers are a more accurate measure of participants' activity neighbourhoods, based on actual potential routes available (along a street network) as compared to the traditional circular (Euclidean) buffers [29]. Also, 25 of the 63 studies were rated as "probably high" risk of bias due to modelling exposures based on geocodes of predefined administrative units. Census-defined neighbourhoods cannot accurately reflect individual activity neighbourhoods, because of the heterogeneity of built environment conditions within them (such as a census tract area). The value of accurate individualized activity neighbourhoods (street buffers around geocoded dwellings) should be emphasized. The spatial scale of these neighbourhoods (buffer radius) is a crucial criterion for accurate exposure assessment and must be based on prior proof of concept. While there is no standardized guideline for the use of buffer size, it is good practice to conduct sensitivity tests with buffers of different scales, to enhance rigor of evidence. Specifically, attention should be paid to issues such as (1) sufficiency of participants having access to specific destinations within the buffer and (2) sufficiency of these destinations within the sampled area [102]. Besides residential neighbourhoods, future studies should also examine the role of built environment attributes within work place- and school-neighbourhoods in influencing cardiovascular risks, given that a significant proportion of time are also spent within them over the life course.

Accurate assessment of built environment exposures over time in observational cohort studies has been a challenge in environmental epidemiology [33]. The application of multispectral satellite and geospatial data facilitates the creation of standardized metrics to objectively measure and quantify participants' neighbourhood built environment, which can be scaled-up and replicated across cohorts at relatively low cost [103]. Due consideration should be made with respect to the spatial and temporal resolution of the data employed. Poor spatial resolution of satellite-derived built environment metrics may result in more study participants being linked to same exposure characteristics (homogeneity) and consequent exposure misclassification. Residential greenness measures derived from MODIS data produce NDVI grids of relatively low resolution ranging between 250 and 500 m, and at the same time, its high temporal resolution implies that it can support almost daily observations. Trade-offs between spatial and temporal resolution should be carefully guided by rate of change of landscape characteristics being measured. On the other hand, studies employing NDVI generated from Landsat and ASTER data have moderate spatial resolution of 30 and 15 m, respectively. Other criteria related to the quality of satellite data such as extent of cloud cover, atmospheric distortion, seasonality and degree of temporal match between outcome ascertainment and exposure assessment [104] are important determinants of accuracy of exposure measurement. In addition to reliance on objective measurements of built environments, future studies should also explore of individual perceptions in influencing usability of built environment and their associations with cardiovascular risks [105].

The temporal frequency of exposure assessment is an important consideration in longitudinal studies. One-third (8/24) of the longitudinal studies examining associations between greenness and walkability measured exposures at a single time point. Of the 16 studies that measured exposures at multiple time points, only five studies assigned the exposure value for each address at each follow-up (to account for changes in residential movement). Changes in urban environments over time as well as participants' long-term trajectories of residential mobility should be considered in longitudinal studies to enhance the precision of investigating long-term effects of urban environments on disease development [29, 106].

The underlying mechanisms of the association between urban built environment and cardiovascular health have not yet been well-established and is an active area of research. One of the possible pathways from urban built environment exposures to cardiovascular health is likely to be mediated via chronic stress. It has been suggested that chronic stress may activate and ignite reactions in the primary biological system — the hypothalamic-pituitary-adrenocortical and sympatho-adrenomedullary axes, which in turn initiates physiological alterations including increased heart rate and energy consumption, thereby increasing risks of CVDs [107]. Exposure to residential greenness maybe associated with CVD risks via their effects on the oxidative stress [108, 109] and DNA methylation [110]. Greater accessibility to neighbourhood greenspace has also been known to positively influence intention to visit and facilitate mental recovery and restoration [111, 112]. The presence of public open space around home may also help create informal encounters as well as opportunities for social interactions, which may benefit psychological well-being and reduce risks of CVDs [113, 114]. The observed protective effects may also be explained via a physical activity-mediated mechanism; residing in neighbourhoods of higher green exposure and walkability has been evident to be associated with higher physical activity [100, 115, 116]. The protective effects of physical activity on cardiorespiratory fitness, hypertension and arterial wall damage are well-evidenced [117, 118]. Increased intensity and volume of physical activity have been found to be associated with consistent reduction in oxidative stress [119]. The oxidative process induced by reactive oxygen species is important in the pathogenesis of atherosclerosis, the primary disorder resulting in heart attack and ischemic stroke [120]. A well-designed neighbourhood with connected walkways and adequate provisions of services and destinations may incentivize active travel and play an antioxidant role in maintaining cardiovascular health [31]. Further studies are needed to elucidate the underlying mechanisms for the associations between urban built environment and cardiovascular health.

Conclusion

CVDs constitute the leading cause of mortality and morbidity globally and is characterized by complex multi-factorial aetiology. This systematic review found moderately consistent evidence of the protective associations of walkability and greenness with cardiovascular risks and major CVD events.

Downstream built environment interventions in the form of well-designed multifunctional green and walkable neighbourhoods may be long lasting environmental exposures for good that affect significant proportion of the population. Planning and provisioning healthy urban spaces have the potential for direct long-term cumulative effects on population health, as well as indirect ones, in terms of configuring other exposures such as pollution, degree and quality of social connections. Though the effect sizes of the associations with built environment may be small, interventions in built environment have the potential to lower the population distribution of chronic diseases including CVD risks, thereby reducing the associated health burdens [121, 122].

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