Quantifying potential contributions of green facades to environmental justice: a case study of a quarter in Berlin

Esther S. Felgentreff[1] · David Cochius[1] · Thomas Nehls[2] · Jan-Hinrich W. Quandt[1] · Emil J. Roesch[1]

Abstract

The potential of green facades (GFs) to enhance environmental justice (EJ) has not been quantified so far. EJ in Berlin, Germany is assessed by the core indicators (1) noise pollution, (2) air pollution, (3) bioclimatic stress, (4) provision of green space and (5) social status. Most of the inner city is rated "poorly" in one or multiple indicators. Based on literature and spatial data, status quo and target values are determined for indicators (1)-(4) for an exemplary, highly burdened quarter in Berlin. It is assessed if and how much GFs could potentially improve current EJ levels. The improvements due to GFs to reach target values are assessed in % for day/night and indoor/outdoor settings. It can be shown that installing GFs would improve statuses of the four indicators to different extents, with the biggest enhancement found regarding indicator (3) for indoors at daytime: 52%. Determining factors for the EJ improvement potential of GFs need to be further assessed. This feasible method for increasing the amount of urban green can be helpful for improving life in highly burdened quarters. Therefore, from the point of view of EJ, large-scale implementation of GFs in urban areas is recommended.

Keywords Environmental justice · Green facades · Noise pollution · Air pollution · Heat stress · Urban greenspace

Introduction

Anthropogenic activities are altering ecosystems on earth to an unprecedented extent (Foley 2005; Steffen et al. 2015), generating environmental burdens that are unequally distributed across society and especially counteracting the well-being of vulnerable groups (MEA 2005; UNDP 2014; UNEP 2019).

Developing as a grassroot movement in the USA in the 1980ies (Bullard and Johnson 2000), the concept of environmental justice (EJ) now serves as a framework for understanding and addressing the issue of unequally distributed environmental burdens. The US' Environmental Protection Agency (EPA 1998, p. 2) defines it as "[t]he fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental

laws, regulations, and policies. Fair treatment means that no group of people […] should bear a disproportionate share of the negative environmental consequences resulting from [human activities]". Especially in urban areas, people with low income and a low social status index experience disproportionate exposures to environmental stressors by often being constrained in the choice of their living environment, leading to adverse health effects and lower quality of life (Corburn 2017; Allen et al. 2019).

This topic is also gaining recognition in Germany (UBA 2009), where in recent years the state of Berlin developed an approach to map EJ by assessing the following five core indicators, categorizing the status of each indicator as low, medium, or high: (1) noise pollution, (2) air pollution, (3) bioclimatic stress, (4) provision of green space and (5) social status (SenStadtUm 2015a). Acknowledging that it is also possible to assess EJ differently than through these indicators, we adopted Berlin's concept for this paper. It is not the aim of this paper to question, discuss and improve this EJ concept.

An approach to assess patterns of EJ more differentiated than the three classes used by Berlin's senate is proposed by Lakes et al. (2013), who use the example of Berlin to develop an index to quantify the relative degree of EJ of

✉ Esther S. Felgentreff
esther.felgentreff@posteo.de

1 Institute of Ecology, Technische Universität Berlin, Berlin, Germany

2 Institute of Ecology, Chair for Ecohydrology and Landscape Evaluation, Technische Universität Berlin, Berlin, Germany

residential areas on the level of planning units. We however decided to use the official calculations of the Berlin Senate as a baseline here.

In line with this, the World Health Organization (WHO) (2011, 2018b) outlines environmental noise, and in particular road traffic noise, as one of the top environmental risks to health, linking it to sleep disturbance, cognitive impairment, or cardiovascular disease. In Germany, over 20% of the inhabitants within urban areas are exposed to noise levels harmful to health (EEA 2020). Further, air pollution is estimated to be related to 4.2 million premature deaths worldwide in 2016, even though the emitted amount has been declining for about two decades (WHO 2018b). In this regard, particulate matter ≤ 2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2) emitted by energy production, traffic, or industry are two of the main health threatening substances, being associated with increased bronchitis symptoms, reduced lung function, cardiovascular and respiratory diseases, or different kinds of cancer (WHO 2018b). The third indicator, bioclimatic stress, comprises the sum of all climatic factors that influence the thermo-physiological condition of humans, including air temperature, wind velocity, air humidity, and the incoming solar radiation, referring to a state of thermal discomfort. This can lead to so-called "heat stress" or "cold stress" (Matzarakis and Mayer 1996; Matzarakis and Amelung 2008; Mayer et al. 2008; SenStadtUm 2011, 2015a), whereby here and in the following, only heat stress will be considered. Due to the urban heat island effect, this is a problem especially in urban areas (Dimoudi et al. 2013). Heat stress has several adverse health effects and causes numerous deaths (Matzarakis and Mayer 1996; Robine et al. 2008; Gabriel and Endlicher 2011). Particularly the lack of nightly indoor cooling leading to partial sleep disorder is thought to play a major role (Nicholls et al. 2008; Kenny et al. 2019). Additionally, the provision of green space comes into focus as green urban spaces are highly valued for their recreational purposes, allowing a certain compensation of the environmental burdens experienced in densely built areas or serving for environmental education. Today, in the context of urbanization and climate and demographic change, there is even more pressure on greenspaces within cities to fulfil multiple purposes with as little cost as possible (Garske 2011). While vertical green spaces are obviously different to horizontal green spaces, it can be expected that vertical ones provide important ecosystem services especially in densely populated areas with deficient green space provision. As in these quarters, new parks are unlikely to be built, it is worthwhile to assess the potential of green facades (GFs) as an implementable option to improve the living conditions.

Eventually, the fifth indicator social status is not a direct environmental burden and cannot be thought to be improved by a change in nearby green space. However, it demonstrates high vulnerability when coming together with one or more of the other four indicators and puts them in the context of EJ.

In the assessment of EJ in Berlin, most of the inner city is rated "poorly" in one or multiple of the indicators, emphasizing the need for structural improvement measures. Research suggests that vertical greenery systems (VGSs) can positively influence indicators (1)-(4) – whereby indicator (4) needs to be discussed in further detail (Ottelé et al. 2010; Wong et al. 2010a; Hoelscher et al. 2016; Radić et al. 2019) – but not the indicator (5), social status.

This study aims at quantifying the maximum potential of green facades as one type of VGSs to enhance EJ as this has not been done so far. Contrary to living walls (LWs) which consist of vertical panels or geotextile felts with a growing medium for low growing plants which typically develop on a horizontal base, GFs usually apply climber plants planted at the base of a building, using its facade or trellises or ropes as growing support (Pérez et al. 2011; Perini et al. 2013). There exist different nomenclatures for facade greening techniques, but this study follows the nomenclature where "VGS" is the generic term for all types, and "GFs" and "LWs" are the two subtypes as described by Radić et al. (2019).

LWs, however, require considerably higher installation and maintenance costs than GFs, making their large-scale implementation in low-income areas infeasible (Perini and Rosasco 2013). Regarding the intention of improving EJ, this study focuses on GFs, due to their easier implementation, higher data availability and lower structural complexity, which allows for better comparability between the investigated factors. Fear of facade damage due to VGS, which accounts especially for GFs, is a misconception, as plants growing and rooting directly at a facade only pose a risk if walls are already damaged (Ottelé 2011).

No matter which greening system is used, it should be noted that greening the whole facade area is not realistic. This is not only due to architectonic features such as windows, balconies, etc. but also because of sustainability concerns such as limited water availability (Pearlmutter et al. 2021).

In this study, based on literature and spatial data, status quo and target values to reach EJ are determined for the indicators (1)-(4) for a highly burdened exemplary quarter in Berlin. We purposely exclude indicator (5), social status, from the calculations, as installing a GF will obviously not affect the social status. However, we choose an exemplary quarter with a low social status index, as it is

the limited adaptability capacities of these communities that require discussions of EJ but also proactive reductions of environmental burdens.

Subsequently, the maximum potential contribution of GFs to achieve the set target values is assessed and quantified for the examined indicators.

Materials and methods

An exemplary street in the district *Berlin-Gesundbrunnen* was chosen as the case study site. In the Environmental Justice Atlas, this site is classified as highly burdened, as it is categorized as medium burdened by noise pollution, highly burdened by air pollution and heat stress, has low access to green space, and a low social status index (SenSW 2015). In this area, residential buildings from the Wilhelminian period built in perimeter block type are prevalent. This type is the most common in Berlin, and roughly a third of Berlin's residents live in such buildings (SenS 2011). The area and these buildings can therefore be considered representative of a highly environmentally burdened, however typical Berlin housing situation.

The example buildings presumed for this study are 22 m high, 10 m wide and have four storeys. We analyzed a street canyon with two rows of such buildings with the ratio of height to width = 1, meaning that the street width is 22 m. A 40 m long section of this canyon is looked at, i.e., four houses as described above on either side of the street.

The 'status quo' was investigated by collecting status quo values for the four indicators based on available information from the municipality of Berlin. We then assume a potential 'greened case' in which this canyon section is greened hypothetically. 70% of the street-facing walls of the example buildings are assumed to be eligible for greening, while the remaining 30% are windows and doors (Loga et al. 2011). The area of the greened facades for the two sides of the street is therefore 40 m x 22 m x $0.7 \times 2 = 1232$ m^2. The utilized plant *Parthenocissus tricuspidata* (Boston ivy) is commonly used on facades (Preiss 2013). This study refers to a period in which the plant bears leaves. It is assumed that no street trees are present in the section to avoid mixing the effects of trees and the GF. For each indicator, values for this predicted 'greened case' were determined.

Then, 'target values' which describe a desirable target state of these indicators were researched. It is assumed that if the status quo value equals or exceeds the target value, EJ would be "achieved". The differences between status quo and target values were determined as the "gaps" which must be closed to "achieve" EJ. The difference between the status quo value and the predicted greened case contribution is referred to as the 'EJ-improving potential of GFs',

calculated as contribution in % of the full "gap", described above. Wherever possible, a distinction was made between day and night as well as between indoor and outdoor.

Noise pollution

The evaluation of the EJ improving potential of GFs regarding the indicator noise pollution is based on a literature review. Regarding attenuation effects, the focus in this study lies on urban road traffic noise with relatively low speeds and a main frequency spectrum at low to middle frequencies around 500–1000 hertz (Hz) (Feldmann and Volz 2000; Nilsson and Forssén 2013), as this is the most dominant source of urban noise and its associated adverse health effects (van Kempen and Babisch 2012; EEA 2020). The status quo values for the exemplary quarter were derived from the maps *07.05.1 Strategische Lärmkarte LDEN Straßenverkehr* (SenSW 2017) and *07.05.2 Strategische Lärmkarte LNight Straßenverkehr* (SenSW 2017) of the geodata portal FIS-Broker. The dominant outdoor sound pressure levels at the facades are 75 A-weighted decibel (dB(A)) at day and 65 dB(A) at night (data for 2017). For indoor sound pressure levels, a default attenuation of -21 dB(A) compared to outdoors was assumed, as described in the *Good Practice Guide on Noise Exposure and Potential Health Effects* (EEA 2010). This results in status quo indoor sound pressure values of 54 dB(A) at day and 44 dB(A) at night.

These values were compared with target values for environmental noise set by the WHO to prevent adverse health effects, recommending outdoor sound levels not exceeding 55 dB(A) at day and 45 dB(A) at night. For indoor sound levels, target values of 35 dB(A) at day and 30 dB(A) inside bedrooms at night are provided for continuous background noise (WHO 1999, 2009, 2018a). For the noise reduction potential of GFs, existing research on noise attenuation effects of VGSs was examined to derive precise values in db(A). These values relate to the attenuation in sound pressure due to installing GFs.

The value for outside noise reduction by GFs found in literature with best comparability to the depicted exemplary conditions in this work was modelled for a 400 m long street canyon with 16 m width and 20 m high fully vegetated building facades on both sides. The noise immission was determined at a height of 2 m. Outdoor sound pressure levels are stated to be around 1.5 dB(A) lower with this type of VGS (Feldmann and Volz 2000). The indoor noise attenuation potential of GFs refers to an *in-situ* measurement of its acoustic insulation capacity according to the UNE-EN ISO 140-5 standard, conducted at a cubicle of 3 m width, length, and height. A double-skin GF was installed by attaching a simple wire mesh covered with a 0.2–0.3 m thick layer of vegetation with *P. tricuspidata* parallel to the wall of the cubicle in a distance of 0.25 m. For the measurements inside

the cubicle, noise was emitted by a speaker 2.3 m in front of the facade at a height of 1.2 m. In this study, an increased sound insulation of 1 dB(A) for traffic noise indoors was found (Pérez et al. 2016).

Air pollution

Status quo values for the key indicator air pollution were taken from the FIS-Broker map *Umweltgerechtigkeit: Kernindikator Luftbelastung (Umweltatlas)* on EJ (annual means for 2009) (SenStadtUm 2015b). Therefore, concentrations of 32.11 μg/m^3 NO$_2$ and 23.44 μg/m^3 PM$_{2.5}$, respectively, are used for both day and night. To determine target values for an 'environmental just' status, threshold values set by the European Union and the WHO were compared to the target values in the EJ monitoring of Berlin (WHO 2018b; SenUVK 2019; UBA 2019). The lowest set values found in one of the three previously mentioned sources were taken as target values for this study. These are 17.1 μg/m^3 NO$_2$ from the EJ report and 10 μg/m^3 for PM$_{2.5}$ from the WHO (2018a).

Pugh et al. (2012) calculated specific values for the reduction of NO$_2$ and PM$_{10}$ concentrations by green walls using a model simulation. The simulation took place in central London, UK which has a similar climate to Berlin (Pfadenhauer and Klötzli 2014). Reduction potentials as shown in the graphs are 2.7 μg/m^3 for NO$_2$ and 3.3 μg/m^3 for PM$_{2.5}$. Pugh et al. (2012) do not consider the reduction of PM$_{2.5}$, but as other research suggests, it can be expected to even exceed PM$_{10}$ reduction (Vardoulakis et al. 2003; Litschke and Kuttler 2008; Ottelé et al. 2010). We however assumed that PM$_{2.5}$ and PM$_{10}$ do not differ, so that the calculation of Pugh et al. (2012) could be used. Indoor air pollution reduction by GFs has hardly been researched so far, hence no values are calculated for this part of the study.

Heat stress

Buchin et al. (2016) developed an equation to calculate the indoor temperature at time $t + \Delta t$ of a building:

$$T_{in}(t + \Delta t) = T_{out} + \lambda I + (T_{in}(t) - T_{out} - \lambda I)\exp(\frac{-\Delta t}{\tau}) \quad (1)$$

$T_{in}(t)$ = indoor temperature at time t; T_{out} = outdoor temperature;
λ = solar temperature elevation constant;
I = incoming horizontal radiation; τ = time constant

They adjusted Eq. (1) to be specifically for the second floor of a west exposed residential Wilhelminian building, being partly shaded by other buildings (i.e., not free-standing). They modelled the building in the simulation program EnergyPlus, entered climate data, and simulated indoor temperatures. With these, Eq. (1) was parameterized and calibrated, yielding values for the two parameters τ and λ ($\tau = 4.115*10^5$ s, a measure for the thermal inertia of the building, and $\lambda = .025$ m^2 K/W, representing the temperature elevation due to solar gains) (Buchin et al. 2016).

Buchin et al. (2016) shared the weather dataset they used for their calculations with us, consisting of hourly measured temperatures in Potsdam from the Deutsche Wetterdienst (DWD) and global horizontal short-wave radiation data from a weather station at Technische Universität Berlin in Berlin-Steglitz (Buchin et al. 2016). Here, data from summer 2003 was used, which was a record hot summer in many parts of Europe (Robine et al. 2008) and during which Berlin also experienced several consecutive hot days. Indoor temperatures were calculated using Eq. (1). The heating period during which the indoor temperatures are determined by a heating system was set to end April 30 and begin October 1 (Mieterschutzbund Berlin e.V. n.d.). The observed period was set to May 1–September 30, and it was assumed that there was no air conditioning or other cooling measure. Indoor temperatures during the heating period were assumed to be 22 °C during day and 18 °C during night, meaning that at midnight on April 30, 18 °C was the present indoor temperature when calculations of the indoor temperatures began on May 1, 1:00 am. The temperatures were calculated in hourly resolution. Then, daily and nightly mean values were calculated for each day from hourly data, from 6 am to 9 pm and 10 pm to 5 am, respectively. The temperature profiles are visualized in graphs. The highest of these mean values was taken as the status quo value.

For daytime, the WHO's Guidelines on Healthy Living recommend 25 °C maximum in temperate regions (WHO 2018c). Different approaches to setting a target value for night-time temperature exist. Here, it is set to 24 °C (CIBSE 2006 as cited in Kenny et al. 2019).

No effect of the GF on the outdoor temperatures is assumed (Hoelscher et al. 2016). Hoelscher et al. (2016) found over 80% of the cooling effect on a building to be caused by shading, especially during hot summer days. As the evapotranspiration cooling effect mainly depends on water supply, only shading is considered. It should be noted that the actual effect can be assumed to be even higher than calculated here. This shading effect of the plants is approximated by lowering the incoming solar radiation I by an additional factor β (2).

$$T_{in}(t + \Delta t) = T_{out} + \beta\lambda I + (T_{in}(t) - T_{out} - \beta\lambda I)\exp(\frac{-\Delta t}{\tau})$$
$$(2)$$

$T_{in}(t) =$ indoor temperature at time t; $T_{out} =$ outdoor temperature;

$\beta =$ additional factor to account for facade greening;

$\lambda =$ solar temperature elevation constant;

$I =$ incoming horizontal radiation; $\tau =$ time constant

Through the 30% of the facade which is uncovered, the solar radiation arrives unfiltered, while on the remaining 70% it is reduced by the plants. Transmissivity of *P. tricuspidata* was calculated to be 0.386 based on Monsi ([2004](#)) and own measurements for leaf area index (leaf surface per wall surfacae, LAI) (1.9) and the attenuation coefficient k (0.5). For that, photos of the facade greening were taken in front of a reference plate mounted between the plants and the wall. Leaves were cut and its areas determined using a xerox and image analysis. The leaf areas were divided by the reference plate area to calculate vertical LAIs. The attenuation coefficients were derived from analyses of images regarding the leaf orientations.

The radiation still arriving at the facade is described with the factor β:

$$\beta = 0.3 * 1 + 0.7 * 0.368 = 0.5702 \tag{3}$$

With this, the indoor temperatures for the greened case were calculated. The EJ-improving potential of GFs was determined as described in 2.1. As the objective was to study the full potential of GFs, the maximum improvement was used.

Provision of greenspace

The data on greenspace and population density in the exemplary quarter was downloaded from the Berlin geodata portal FIS-Broker. It includes the maps *Grünanlagenbestand Berlin (einschließlich der öffentlichen Spielplätze)* (SenSW [2020](#)) and *Einwohnerdichte 2018 (Umweltatlas)* (SenSW [2019](#)) as well as the encoded attribute data on the area extent of greenspaces, population density in each block.

A guideline for sufficient greenspace supply and a definition of the desired proximity of greenspace to people's homes is provided by the Senate Administration for Urban development and housing of Berlin. It was published in 1995 as *Versorgung mit öffentlichen, wohnungsnahen Grünanlagen* and still acts as a measure of greenspace supply in Berlin, e.g. for its targets for EJ (SenStadtUm [2015a](#)) and provides the values for Table [1](#). It should be noted that the guideline differentiates between two types of accessibility, smaller greenspaces close to residents' homes and larger greenspaces within the area. Vertical greenspaces are not explicitly excluded in this guideline. The different functions fulfilled by horizontal versus vertical green spaces are compared in the discussion.

Table 1 Provision of green space rate per capita for open spaces in the catchment areas, a planning basis according to the Senate Administration for Urban development and housing of Berlin

	Greenspace close to home	Greenspace close to residential area
Minimum size	0.5 ha	10 ha
Reference value	$\frac{6m^2}{\text{resident}}$	$\frac{7m^2}{\text{resident}}$
Maximum distance	500 m	1000 m

The data was downloaded and processed using the software QGIS (v.3.12.2-București). As preparation for analysis, an exemplary block was chosen and a line shapefile created, representing the modelled GF. Then, buffers of 500 m and 1000 m were created to delineate the catchment areas as described in Table [1](#). The minimum size requirements for the area of greenspaces to be counted were not applied, as except for one big park, they would have concluded that there was no greenspace in the study area and made it impossible to measure anything. As the GF covers an area smaller than the proposed minimum values and as in this study, small-scale effects are investigated, these minimum values were neglected.

Consequently, the number of inhabitants and the area of greenspace within 500 m and 1000 m were calculated from the aforementioned attribute data. Equations ([4](#))–([6](#)) were applied to calculate EJ-improving potential of GFs.

$$\frac{G}{I} = S \tag{4}$$

$G =$ Area of greenspace within a 500 m radius; $I =$ Number of inhabitants within a 500 m radius;

$S =$ Status quo greenspace per capita ratio in $\frac{m^2}{person}$

$$\frac{G + F}{I} = P \tag{5}$$

$G =$ Area of greenspace within a 500 m radius; $F =$ Area of GF in greened case; $I =$ Number of inhabitants within a 500 m radius;

$R =$ Greenspace per capita ratio in $\frac{m^2}{person}$ in greened case

$$\frac{R - S}{T - S} = EJIP \tag{6}$$

$R =$ Greenspace per capita ratio in $\frac{m^2}{person}$ in greened case; $S =$ Status quo greenspace per capita ratio in $\frac{m^2}{person}$; $T =$ Target value in $\frac{m^2}{person}$; $EJIP =$ EJ-improving potential of GFs

Results

Noise pollution

We found an EJ-improving potential by GFs of 1 dB(A) or 5.3% during day and 1 dB(A) or 7.1% during night for indoors. For outdoors, we calculated an EJ-improving potential by GFs of 1.5 dB(A) or 7.5% during day and night (Table 2).

Air pollution

The pollutant concentration reduction corresponds to an EJ-improving potential of GFs of 18.2% NO_2 and 24.4% $PM_{2.5}$, respectively (Table 2). Hence, the mean improvement for indicator air pollution can be stated to be 21.3% for a combination of both pollutants. Since the status quo values are annual means, the same air quality improvement is assumed for day and night. As specified in 2.2, no values for indoor pollutant reduction could be calculated.

Heat stress

Temperature values over the summer period of 2003 are shown in Figs. 1 and 2. Note that these are mean values,

and higher peaks during the afternoon are attenuated. Three hotter periods during early June, mid-July and beginning to mid-August are visible. In early May, daily indoor temperatures (long dashed lines) were approximately average outdoor temperatures, but after a few days the building heats up and the indoor temperatures of the building with the blank facade (status quo values) remain slightly higher than the outdoor temperatures. Generally, indoor temperature values are subject to less fluctuation than outdoor temperatures.

Predicted indoor temperatures in the greened case (solid lines) are visibly lower than those behind the blank facades. While both temperature profiles begin with the same start value on May 1 after the end of the heating period, they separate soon and the blank building heats up more and quicker. Generally, both curves run quite parallel. The difference between the indoor temperatures of the blank and the greened building increases with higher outdoor temperatures.

With 31.2 °C, the highest daily indoor mean temperature during summer 2003 in Berlin occurred on August 13. As the daytime indoor target value is 25 °C, there is a difference of 6.2 °C. The maximal difference between indoor temperatures with and without GF during daytime was 3.2 °C, occurring on both June 13 and 14. The EJ-improving potential of GFs to close the gap between status quo and target

Table 2 Status quo and target values of the four examined indicators of Environmental Justice and contribution of Green Facades (GF) at different daytimes, indoor and outdoor

Indicator	Location	Time	Status quo value	Target value	Difference between status quo and target value	EJ-improving potential by GFs	
Noise Pollution	Indoor	Day	54 dB(A)	35 dB(A)	19 dB(A)	1 dB(A)	5.3%
		Night	44 dB(A)	30 dB(A)	14 dB(A)	1 dB(A)	7.1%
	Outdoor	Day	75 dB(A)	55 dB(A)	20 dB(A)	1.5 dB(A)	7.5%
		Night	65 dB(A)	45 dB(A)	20 dB(A)	1.5 dB(A)	7.5%
Air Pollution	Indoor	Day/$PM_{2.5}$	-	-	-	-	-
		Night/$PM_{2.5}$	-	-	-	-	-
		Day/NO_2	-	-	-	-	-
		Night/ NO_2	-	-	-	-	-
	Outdoor	Day/$PM_{2.5}$	23.4 µg/m^3	10 µg/m^3	13.4 µg/m^3	3.3 µg/m^3	24.4%
		Night/$PM_{2.5}$	23.4 µg/m^3	10 µg/m^3	13.4 µg/m^3	3.3 µg/m^3	24.4%
		Day/NO_2	32.1 µg/m^3	17.1 µg/m^3	15 µg/m^3	2.7 µg/m^3	18.2%
		Night/ NO_2	32.1 µg/m^3	17.1 µg/m^3	15 µg/m^3	2.7 µg/m^3	18.2%
Heat Stress	Indoor	Day	31.2 °C	25 °C	6.2 °C	3.2 °C	51.6%
		Night	31 °C	24 °C	7 °C	3.1 °C	44.3%
	Outdoor	Day	-	-	-	-	-
		Night	-	-	-	-	-
Provision of green space	Indoor	Day	-	-	-	-	-
		Night	-	-	-	-	-
	Outdoor	Day	3.8 m^2/ person	6 m^2/ person	2.2 m^2/ person	0.016 m^2/ person	1.6%
		Night	3.8 m^2/ person	6 m^2/ person	2.2 m^2/ person	0.016 m^2/ person	1.6%

Fig. 1 Daytime (6 am-9 pm) mean outdoor (short dashed line) and calculated indoor temperatures of a blank facade (status quo; long dashed line, data is taken from Buchin et al. 2016) and a greened facade (greened case; solid line) of a typical Berlin residential building between May 1 and September 30, 2003. The values for each day are calculated as the mean of hourly data between 6 am and 9 pm. No effect of green facades on the outdoor temperature is assumed
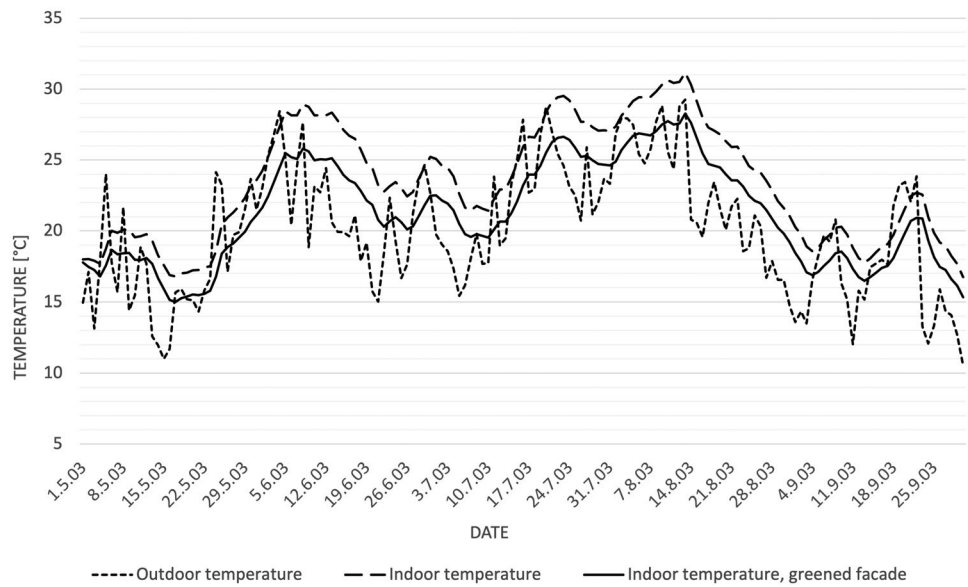
value at daytime can therefore be quantified with up to a maximum of 51.6% at the hottest period of the day (Table 2).

The highest nightly indoor mean temperature during summer 2003 in Berlin occurred as well on August 13 at 31.0 °C. As the night-time target value is 24 °C, there is a difference of 7 °C. A comparison of Fig. 1 and 2 clearly shows how the outdoor temperatures cool down during the nights, whereas the indoor temperatures drop little or not at all, visualizing the trapped heat within buildings and the lack of night-time cooling.

The maximal difference between indoor temperatures with and without GF during night-time was 3.1 °C,

occurring in the nights of June 9, 10, 13 and 14. The EJ-improving potential of GFs at night-time can therefore be quantified with up to 44.3% (Table 2).

Provision of greenspace

Figure 3 shows the catchment area, the position of the GF and the buffer areas. For the 500 m catchment area, the potential improvement was 1.6%. The 1000 m catchment area was already above the target value, so no improvement could be simulated.

Fig. 2 Nighttime (10 pm-5 am) mean outdoor (short dashed line) and calculated indoor temperatures of a blank facade (status quo; long dashed line, data is taken from Buchin et al. (2016) and a greened facade (greened case; solid line) of a typical Berlin residential building between May 1 and September 30, 2003. The values for each night are calculated as the mean of hourly data between 10 pm and 5 am. No effect of green facades on the outdoor temperature is assumed
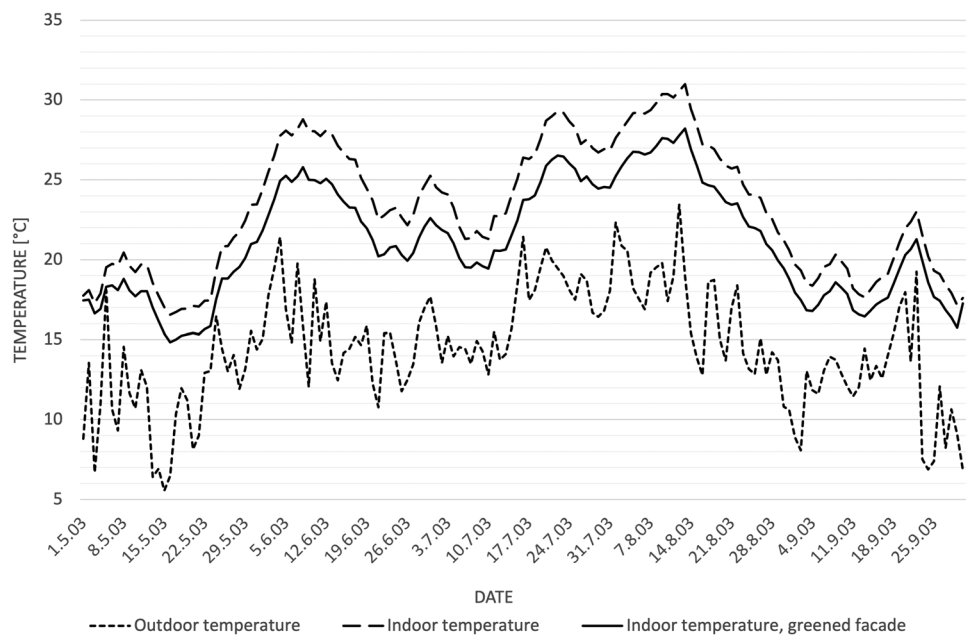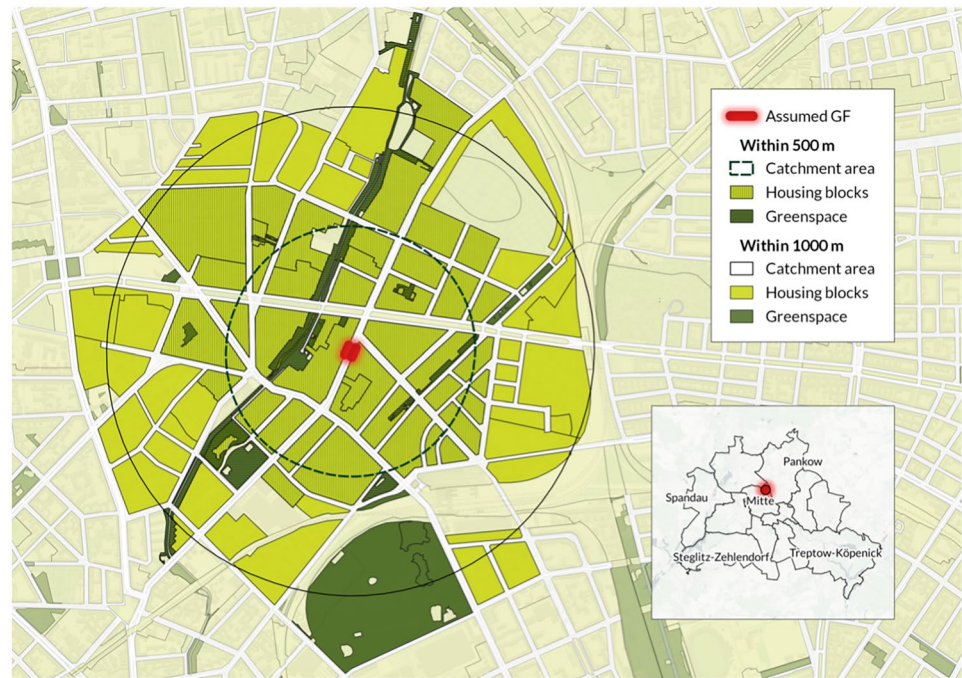
Fig. 3 Modelled green facades (GF) in Berlin-Gesundbrunnen with 500 m and 1000 m parameters and the according housing blocks as well as greenspaces; Created in QGIS (v.3.12.2-București), using data from FIS-Broker (SenSW 2018, 2020)

Discussion

The results regarding the **noise pollution** attenuation potential of GFs show that vegetated street canyons reduce the propagation of road traffic noise, although their contribution is rather limited and does not exceed 1.5 dB(A) (see Table 2). This is partly explained by the aboveground vegetation components such as leaves and stems that absorb and scatter sound mainly at high frequencies (Wong et al. 2010b; Yang et al. 2013; Pérez et al. 2016). The acoustic effectiveness of GFs is therefore relatively small in the low frequency spectrum of road traffic noise (Forssén et al. 2014). Furthermore, noise reduction levels of up to 8 dB(A) or more that are attributed solely to plant materials in literature, usually assume vegetation belts of a few meters depth that are relatively rich in biomass (Cook and van Haverbeke 1975; Van Renterghem et al. 2012). These values are unrealistic to be achieved in the limited space of urban street canyons.

Nevertheless, even the stated values should be treated with care as real conditions foster complexity and many factors influence the acoustic performance of GFs. Accordingly, not only characteristics of the environment and the noise itself impact the acoustic performance of VGSs but also plant-related factors. For example a larger amount of foliage, leaf area density, or dominant angle of leaf orientation results in an improved noise reduction capacity (Wong et al. 2010b; Horoshenkov et al. 2013; Nilsson and Forssén 2013). Although this study focussed on GFs, we would like to add that also the presence of substrate as part of a LW can substantially enhance the acoustic performance of VGSs in

lower frequencies, as shown by Azkorra et al. (2015), Pérez et al. (2016), Wong et al. (2010b). The latter measured noise reductions of around 5–10 dB for different types of VGSs.

However, a consistent conclusion cannot be drawn as studies regarding the noise attenuation effects of vegetation incorporated in buildings usually refer to green roofs and the consideration of VGSs is scarce (Azkorra et al. 2015; Pérez et al. 2016). In addition, due to the wide range of different VGSs and their varying acoustic behavior, the studied types of VGSs as well as the methodologies and outcomes differ considerably, hence hindering generalization (Azkorra et al. 2015). It should be emphasized that also the experimental set-up of the consulted studies partly differed from the assumptions of this work, so that for example the increased street width of 6 m assumed in this study potentially results in a decreased noise reduction potential of VGSs in street canyons (Feldmann and Volz 2000; Forssén et al. 2014). Finally, Van Renterghem et al. (2013) also highlight the dependence of the measured noise attenuation effects of a VGS from the assumption of the material characteristics in the reference case. Consequently, the noise reduction effects of GFs presented in this study should be understood as approximate values revealing the relatively low potential of GFs to contribute to noise attenuation. In this regard, future research should rather focus on noise abatement effects by LWs as their acoustic performance seems to be more promising according to the mentioned studies.

The EJ-improving potential of GFs in mitigating **air pollution** is comparatively high (see Table 2), even though there are numerous determining factors that need to be further

analyzed. Some plants emit biogenic volatile organic compounds (bVOCs) that can add to ozone formation under urban conditions where nitrogen oxide concentrations are high (Matsunaga et al. 2017; Fitzky et al. 2019). Leung et al. (2011) and Benjamin and Winer (1998) stated the emission of bVOCs to be especially high when plants are facing water stress, high temperatures and high solar radiation intensities. Most research on this subject focuses on emissions from trees and shrubs. Further investigation of climbing species' emissions is necessary. This also applies to plant pollen emissions, which are another possible health impact of VGSs due to possible allergic reactions. Bergmann et al. (2012) classified urban plants in Berlin in terms of pollen emissions and left out climbing plants completely from his study. Also, particle resuspension, which means removal of particles via wind or rain, is a field that needs to be further investigated (Reznik and Schmidt 2009; Ottelé et al. 2010).

Since *P. tricuspidata* is not evergreen, its EJ improvement potential is hardly applicable for winter. Concurrently, an improvement of air quality is especially important in winter: The urban boundary layer is lower than in summer, leading to a near-surface pollutant accumulation (DWD 2017). Additionally, there are higher emissions in winter due to heating.

The fact that there are no values for the indoor pollutant reduction by GFs is due to lacking research. Nevertheless, there exists a strong correlation between indoor and outdoor pollutant concentrations (Diapouli et al. 2007; Ji and Zhao 2015; Leung 2015): less pollutants in street canyons will lead to lower concentrations indoors. That, however, depends on indoor ventilation: Opening windows leads to higher air exchange rates which lead to similar pollutant rates indoors and outdoors.

Also, no separate values for day and night can be determined since the observed values are long term means. Anyway, it can be presumed that reductions by day will be higher since there are more pollutants present in street canyons because of higher traffic emissions and higher small-scale turbulences during daytime.

The specific number of captured particles and gaseous pollutants also strongly depends on the street canyon ratio and the LAI, rising with higher values for these factors (Pugh et al. 2012; Abhijith et al. 2017). The uptake of other substances is not considered in this study since the Berlin EJ assessment considers only NO_2 and $PM_{2.5}$. Nevertheless, these pollutants are not the only ones being taken up by or settle on GFs. Jayasooriya et al. (2017) also detected an uptake of SO_2, CO and O_3.

GFs can considerably ameliorate the state of indoor **heat stress** in urban areas. The potential of GFs to mitigate heat stress as determined here is the highest of the four indicators (see Table 2). This is in line with numerous studies about the effect of VGS on the temperature of a building (Wong et al. 2010a; Cameron et al. 2014; Hoelscher et al. 2016; Šuklje

et al. 2016). As the heat stress risk will rise in the future due to climate change, an increase of extreme weather events (IPCC 2014), accelerating urbanization and urban densification, thus more intense UHI (UN DESA 2019), and the demographic change (Dugord et al. 2014), the heat stress aspect of EJ will get more and more relevant. The remarkably high reduction of the indoor heat stress by a simple GF underlines its high potential to be applied as climate change adaptation measure.

To investigate heat stress, it is advisable to consider indoor rather than outdoor temperatures. This is because urban vulnerable groups spend 80–90% of their time indoors (Brasche and Bischof 2005; Buchin et al. 2016; Kenny et al. 2019), so they are exposed to indoor heat stress considerably more than to outdoor conditions. Climatic and temperature patterns differ between outdoors and indoors, meaning that conclusions drawn from analyses done outdoors are not transferable to indoor conditions. The comparison between Fig. 1 and 2 visualizes that there is a less considerable effect of night-time cooling indoors than occurring outdoors.

To predict indoor temperatures, we chose a physically based, rather conservative approach by considering only the shading impact of GFs. Simulations on such scale are usually subject to uncertainties. However, we chose the most appropriate approach according to Buchin et al. (2016) and only reduced the incoming radiation by adding factor β. Validation of the model was however out of scope for this study. Despite that, the EJ-enhancing potential of GFs was found to be considerably high here. Future studies should furthermore include the other cooling effects of plants, namely insulation and evapotranspiration, which will likely result in a greater cooling potential by GFs than predicted here.

The assumption that GFs have no effects on the outdoor climate in the street canyon should also be tested again, as existing studies came to different results. While Hoelscher et al. (2016) and Šuklje et al. (2016) could not detect cooling effect of GFs on the street canyon, Djedjig et al. (2013, 2015a, b, 2016) measured in a reduced-scale experiment marginally cooler temperature in greened canyons. Alexandri and Jones (2008) simulated up to 2.5 °C lower temperatures in a street canyon during the afternoon in temperate climates using their micro-scale model. If such a cooling effect of GFs can be proved and quantified, the real indoor cooling potential of a GF could be higher than assessed here.

Even more than GFs, LW systems can be assumed to have a greater cooling effect on the building due to the increased insulation by a thicker layer and additional evapotranspiration by the substrate. On the other hand, the additional insulation could hinder cooling of the building (Pérez et al. 2011). Indoor temperature is not the only component of thermal comfort, but is a sufficient predictor for heat stress (Urban and Kyselý 2014; Buchin et al. 2016). It is therefore

advised to consider mainly the indoor temperature in evaluations and calculations regarding heat stress, and it is recommended to consider indoor rather than outdoor conditions in Berlin's EJ assessment (SenUVK 2019).

Provision of green space stands out from the formerly discussed indicators for EJ, as it does not revolve around adverse health effects. Instead, it can be seen as a valuable resource that can, among other benefits, promote a healthy lifestyle and reduce stress of urban inhabitants (Haluza et al. 2014).

The minimum area sizes for greenspaces (Table 1) to be counted in the analysis were omitted, because the change caused by greening a street canyon would not have been possible to show, as the area of the assumed GF would not exceed the area necessary for it to be included. However, the values also seem relatively high, considering that benefits from GFs are expected (Radić et al. 2019) long before reaching an area this big (0.5 and 10 ha). Therefore, this study argues for a more open approach to urban greening, and a point was made to count all urban green, no matter the size, from the data set.

The radius used for assessing greenspace close to peoples' dwellings was 500 m (and 1000 m close to residential areas, respectively), however as Grunewald et al. (2017) pointed out, they should be in actual walking distance instead of linear distance to not give a wrong impression of how far people will go for short range recreation. In their study, they propose a 300 m radius instead. For this work, it was decided to stick to the radius as chosen by the senate of Berlin (Table 1), however this could have led to a misjudgement of how far people walk to urban greenspace.

The Berlin target value of 6 m^2 greenspace per person within 500 m of their home (SenStadtUm 2015a), as used in this study, seems like a good starting point. It provides a data base to quantify the lack of urban greenspace in certain areas and helps to communicate the need for action. On the other hand, this value seems arbitrarily small, especially when compared to status quo values in other cities in Germany which have a median of 8.1 m^2. While the actual values differ considerably throughout the country, from 2.5 m^2 in Schwerin to 36 m^2 in Bergisch Gladbach (Wüstemann et al. 2016), we think target values should generally be set higher, considering the fundamental role of urban greenspaces for public health, the (micro-)climate and biodiversity. Russo and Cirella (2018), in accordance with the WHO, recommend a minimum target value of 9 m^2/capita and ideally 50 m^2/capita, while recognizing individual solutions for climatic and structural differences. This again indicates how much room there is for improving access to and the overall area of urban greenspace to benefit the public. However, any value should be viewed with a grain of salt as it acts only as a tool to identify insufficient provision of green space, and therefore potential environmental injustice, but should not

be seen as a definite answer, as there is still no consensus on how much is needed or even recommended.

In the analysis, the area extent of GF is compared to horizontal urban green spaces like parks without a distinction. There are obvious differences to GFs though, in contrast to the enterable and tangible nature of a park. In addition, there are more limitations to the types of plants that can be established to grow on or in front of a facade.

Yet, GFs are green spaces. They may not be perceived as green spaces, not because they are of low quality, but because they do not fulfill the corresponding requirements in the guideline (SenStadtUm 2015a). This guideline, however, is insufficient, as it neglects multiple important effects of green spaces such as social benefits (e.g., community gardening), visual and educational effects (e.g., observing wildlife) or habitat provision for wildlife – services that can be provided by vertical green spaces, too (see Radić et al. 2019). Studies by Haluza et al. (2014), Jonker et al. (2014), Reid et al. (2017), Astell-Burt and Feng (2019), and Tost et al. (2019) all showed positive health effects of urban green, especially stress relief. Even though the evidence is not yet highly conclusive on the causal effects, it is feasible that they can be transferred to a certain degree to GFs. Accordingly, Pérez-Urrestarazu et al. (2017) demonstrated positive effects of VGSs on the mental health of hospital patients.

Regarding accessibility issues and greening the direct residential surroundings of inhabitants in densely built quarters, GFs have the advantage to be equally accessible for all – including for those who cannot leave their homes –, being visible from the street and from adjacent buildings. We therefore suggest that a future indicator for assessing provision of green space incorporates these functions.

In reversing the question, not asking how much improvement to green space targets a GF can contribute, but how many facades would need to be greened to reach target values, the extent of the lack of greenspace in the area was demonstrated. Within the 500 m radius of the modelled GF, 2.6 km of street canyons would need to be greened to reach the target value. This GF coverage is difficult to achieve, so it shows the need for action in urban greening. Even with this GF coverage, due to the different properties of horizontal greenspaces and GFs, it is difficult to say if sufficient provision of green space would have been achieved. GFs are a viable, but complementary type of urban green and should not replace greenspaces like parks.

Combinations of multiple stressors can result in interactions, which in turn increase the adverse effects. For example, Golmohammadi and Darvishi (2019) found that the combination of noise pollution, air pollution und heat stress can lead to "hearing loss, hypertension, cardiovascular effects, psychological effects, and sleep disorder". Interactions by multiple stressors should thus be subject of further investigation.

When talking about the properties of GFs, note that the plant species proposed for this study is *P. tricuspidata*, a deciduous plant that loses most of its beneficial properties for the winter months. This plant was chosen as it is one of the most common plants used for GFs in Germany and is often considered in research (Preiss 2013), however, evergreen and similarly common plants like *Hedera helix* should also be considered for a real GF.

There are however some points to discuss. A question coming up is whether justice can even be measured and discussed as something that can be reached partially. Justice is a complex social and philosophical concept but a discussion on its nature goes beyond the scope of this study. Instead, we stuck to the existing definition of EJ (see Introduction). Integration of affected groups in society rather than excluding them from decision-making processes should however be a prerequisite when talking about justice. Further studies dealing with this topic are welcome to critically discuss the approach of quantifying EJ.

Compared to other approaches like green roofs, expensive air filtering technology and cooling systems, GFs are relatively inexpensive and can be installed in many urban settings (Preiss 2013). A potential challenge is the feasibility due to monument protection, as many buildings in Berlin are classical Wilhelminian and permits could complicate the process of GF installation.

As already stated in former parts of this section, LWs might have an even higher potential on mitigation of EJ. They are supposed to reduce noise pollution (Wong et al. 2010b; Azkorra et al. 2015; Pérez et al. 2016) and heat stress (Pérez et al. 2011) substantially stronger than GFs. But they also are more expensive and require more maintenance than GFs, which prevents them from being economically sustainable and attractive in implementation. Even though GFs are among the cheapest options to implement urban green, and the resulting recommendation that this is a good measure, Perini and Rosasco (2013) showed that they could raise the property value of surrounding neighbourhoods. Due to missing or inappropriate political regulations of the housing market this is potentially on the cost of the people (low income, low social status) that should benefit from greening efforts in terms of EJ. Instead, they might be forced to move out of their former neighbourhood. However, such discussions should not cynically hinder installation of GFs but rather demonstrate the need for political regulation. Regarding vulnerable groups or people with a low social status index, it should be recognized that their adaptive capacity to the examined environmental stressors is lower. As stated above, GFs are an attractive measure since they are low in cost and required space and thus possible to be implemented on a larger scale. GFs are neither the solution to environmental injustices, nor are they completely to be dismissed in aiding this challenge, but, as shown in this study, are a valuable addition among other solutions. It should be noted that this is a rather theoretic study, presenting exact figures, which are based on other studies and some model case assumptions. It was our aim to assess the maximum potential impact of GFs to improve EJ. Having shown that this can be remarkable, we suggest further empirical investigations.

Conclusion

In this study, the potential of GFs to contribute to EJ in an exemplary quarter of Berlin was investigated using a novel approach. This study revealed both the enhancement of EJ by GFs, and the possibility to quantitatively assess this improvement.

It was shown that GFs can improve the status of all four investigated indicators to different extents, whereby the effect on indoor heat stress at daytime is with up to 51.6% the largest. The method used in this study proposes a shift of perspectives from outdoors to indoors when researching urban heat stress.

GFs should be perceived as green spaces as they provide numerous ecosystem services. They should therefore be included in green space provision guidelines. Due to GF's comparably low horizontal space requirements, easy installation, and little costs, GFs can be set in place almost anywhere in the city, most likely improving the well-being of adjacent communities. Many different designs of VGSs with varying properties exist, and these systems can be adjusted to the requirements of the respective environment and intended improvements.

Due to the many positive effects and few downsides of GFs, large-scale installation of GFs in urban areas is recommended especially where the status of the four indicators is low. The approach to quantify the improvement potential of GFs aforehand is a starting point for action and further research can build upon that.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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