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High albedo plant selection for mitigation of the urban heat island

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ABSTRACT

The use of greenery as countermeasure to Urban Heat Island phenomenon is one of the more efficient answers to urban warming since it provides significant benefits in terms of thermal comfort and air quality and, therefore, human health. The civil and environmental engineering research is rising the attention to the design of greenery in urban and surrounding areas in order to find out innovative strategies and technologies that can improve the urban climate. Different types of greenery usually exist in the city areas such as parks, green roofs, vertical gardens. The physical and physiological features of plant species involved in greenery systems lead to their effectiveness in terms of thermal mitigation. This study is aimed to investigate the surface radiative properties of green canopy with high albedo such as *Stachys bizantina*, a herbaceous plant characterized by an ashen color due to the presence of a white silky-lanate hair. Its albedo can be especially helpful during heat waves, when plants in green areas often close their stomata and thus reduce significantly evapotranspiration and, with that, their mitigation potential. The albedo of *Stachys b*. has been measured through ASTM E1918, then compared with the albedo of grass commonly used in green urban areas (*Lolium perenne*). Values obtained through field measurements have also been complemented with measurements through a WorldView-3 platform satellite image of the city of Modena, Northern Italy. Replacing partially the grass cover of green areas with high albedo plants like *Stachys b*., indeed representative of other useful species, can yield a non-negligible increase of the urban albedo on these green districts and their surroundings.

Introduction

Today, almost 60% of world's population is living inside cities, and the trend is going to increase (UN 2018). This is the reason why high attention is being paid to the potential influence of the urban environment on climate change. Building materials retain more solar energy during the day and have lower rates of radiant cooling during the night, compared with vegetated surfaces (Wilby 2007). Processes such as industrial manufacturing, building heating and air conditioning, and transport systems contribute to introducing additional heat sources into the urban environment. Moreover, heat dissipation due to wind-induced convective processes and plant evapotranspiration is less effective in densely built cities as a consequence of the lower wind speed and the smaller green areas. All these factors are responsible of the urban heat island (UHI) phenomenon, the most documented one related to climate change. UHI sensibly impacts on citizens' life, and on their health and quality of life. The high rate of energy consumption and pollutants emission for building cooling represents a serious problem also for the economy and the global environmental quality (Santamouris 2014).

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Recently, the building engineering research has invested increasing resources to study and enable solutions for UHI mitigation through greenery (Ross et al. 2014). Urban forestry, parks, street trees, green roofs, gardens, vertical green represent efficient answers to urban warming, providing thermal benefits, air quality, and so human health (Akbari et al. 2001). A comprehensive review study by Santamouris et al. (2018) highlights how vegetation areas can reduce the peak ambient temperature by 1.2 K or 1.5 K by using grass or trees, respectively, while an average increase of the albedo of a given area by 0.2 may lead to an ambient temperature drop of 1.5 K.

The efficiency of greenery to create a cooler environment depends greatly on plants transpiration, which depends in turn on stomatal resistance, as well as on shading and albedo of the foliage canopy(Santamouris et al. 2018): the transpiration process relies upon the release of water vapor from leaves into the air, providing a temperatures drop of the leaves and the surrounding air thanks to the latent heat of the evaporated water (Akbari et al. 2002); this is influenced by parameters such as the leaf area index (LAI), a representation of the plan-form area coverage of the leaves with respect to the underlying ground area. The stomatal resistance controls the rate of moisture transpired by the plant, and therefore the rate of absorbed latent heat (Berardi et al. 2014). However, a non-negligible contribution to heat release can be obtained thanks to relatively high values of the effective albedo, that is the reflectance of the incident solar energy provided by the upper surface of the vegetation canopy layer.

Several research studies are showing how greenery selection is important to implement urban temperature mitigation (Hamada et al. 2010; Bowler et al. 2010). Species-specific morphologic and physiologic plant features influence the evapotranspiration rate of leaves and ground below, and the value of the albedo, two important factors that determine the cooling potential of greenery. This work is particularly focused on the enhancement of greenery albedo, or solar reflectance (ρ_{sol}), in order to improve the mean urban albedo. The albedo of a specific plant species, *Stachys bizantina*, potentially exploitable in most urban green areas and green roofs, has been measured and compared with *Lolium perenne*, representative of commonly used grass species. *Stachys b.* results especially interesting thanks to its morphology and physiology: its leaves are indeed covered by a white-colored hair, which can influence positively the albedo. Its higher albedo values and the cooler foliage canopy can contemporarily contribute to counter urban warming.

Three different standard test methods have been applied to study the solar reflectance of *Stachys b*. Two of them are used to measure the albedo of a single leaf: ASTM C1549, with a solar reflectometer, and ASTM E903, with a UV-Vis-NIR Spectrometer. The albedo of the canopy surface is instead measured according to ASTM E1918A with an albedometer consisting of a dual pyranometer. More details on the test methods can be found in (Muscio et al. 2018). The albedo of the *Lolium perenne*'s canopy layer was also measured on field by a pyranometer, and the acquired reflectance values were then compared with those obtained from a WorldView-3 platform satellite image on test areas in the city of Modena, Northern Italy. *Stachys b.* achieved higher values than those recorded over common grass according to all three standard test methods. Therefore, potential improvements that can be obtained in terms of average albedo increase and local temperature drop through a widespread plantation of whitish colored *Stachys b*. have been assessed. In this regard, the mitigation effect in smaller green area has already been recorded in previous study (Pisello 2016) and shown to be effective for microclimate zone in case of dense and low rising built areas. In fact, the application of high albedo greenery could be especially helpful against UHI on very dense urban areas and surroundings. It is worth to note that *Stachys b*. is not the only plant to have a potentially positive effect on albedo; other species with similar morphology can be assessed: *Jacobaea maritima, Artemisia* spp. and *Helichrysum italicum* (Pisello 2016).

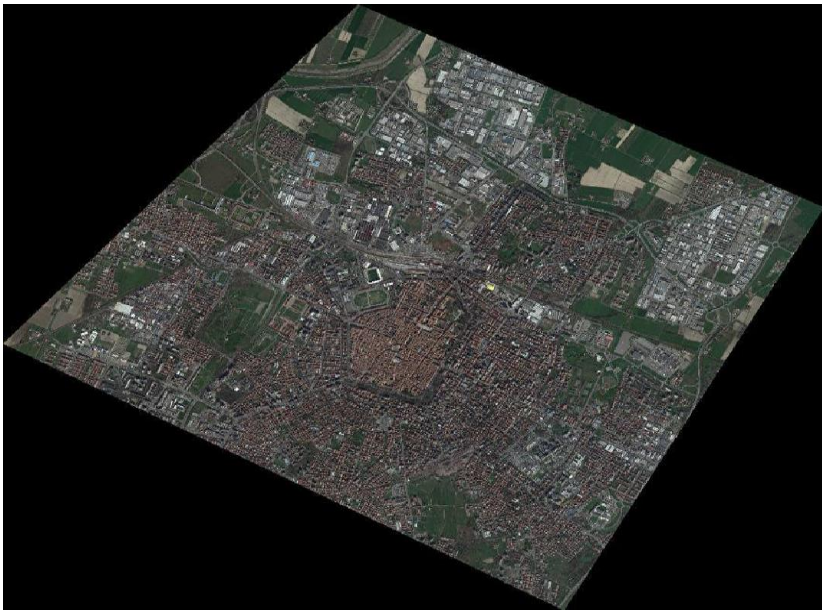

Figure 1: WorldView-3 Image on the urban area of Modena, Northern Italy.

An assessment of the albedo enhancement that can be obtained through the usage of a specific plant species such as the considered one has also been completed with the evaluation of its evapotranspiration potential, depending on its stomatal resistance (Vaz Monteiro et al. 2017; Blanusa et al. 2013). Indeed, several experiments performed under heat wave conditions suggested that the capability of physiological acclimatization and the response to extreme ambient temperature depend also to the reflectance of the leaves [Blanusa et al. 2013; Curtis et al. 2012]. Higher leaves reflectance means less solar radiation absorbed, and a better physiological process of vapor exchange and transpiration, thus a more persistent air cooling potential (Reich et al. 2016; Anderegg et al. 2012]. However, despite the key role of plants' characteristics in determining greenery benefits, the analysis of leaves reflectance and its impact on urban climate and temperatures still lacks (Pisello et al. 2016).

Materials and Methods

The albedo of two representative plants species, *Stachys bizantina* and *Lolium perenne*, have been measured. Three different standard test methods have been used to perform the measurements, and the results have been compared to assess differences between the test methods.

Laboratory characterizations were performed by using a UV-Vis-NIR spectrometer (Jasco V-670) with integrating sphere 150 mm (Jasco ILN-725) according to ASTM E903 (2012), and by a solar spectrum reflectometer (Devices and Services SSR v.6) according to ASTM C1549 (2009).

The spectrometer provides the spectral distribution of the reflectivity ρ_λ, defined as the ratio of reflected part and total amount of incident radiation at the considered wavelength λ [nm]. This is then averaged over the wavelength range relevant to solar radiation (300-2500 nm) to obtain the solar reflectance ρ_{sol}, weighting the spectral values with the standard spectral irradiance of the sun at the earth surface, $I_{sol,\lambda}$ [Wm^{-2} nm^{-1}]:

$$\rho_{sol} = \frac{\int_{300}^{2500} \rho_\lambda I_{sol,\lambda} d\lambda}{\int_{300}^{2500} I_{sol,\lambda} d\lambda} \quad (1)$$

The solar reflectometer calculates automatically the albedo as the average of measurements in several wavelength ranges of the solar spectrum, weighted by the reference solar irradiance.

For both measurements by spectrometer according to ASTM E903 (2012) and by reflectometer according to ASTM C1549 (2014), the tests were performed on a single leaf. Moreover, the irradiance spectrum is the most commonly used one as specified by ASTM E891 (1992) for beam normal solar irradiance (E891BN spectrum). Indeed, the reflectance relevant to solar radiation rejection is not that of leaves but that of the upper surface of the plant canopy layer. To analyze an area of such surface much larger than a single leaf, an albedometer (Kipp & Zonen CM6) has been used according to the so-called E1918A test method (Akbari et al. 2008) This one, indeed a modification of the commonly used ASTM E1918 test method (2015), covers the measurement of solar reflectance of various horizontal and low-sloped surfaces and materials in the field, and it allows reducing the minimum surface area to be analyzed from 4 m^2 as required by ASTM E1918 down to 1 m^2 by exploiting properly colored masks.

On-field measurements on *Stachys b.* canopy have been carried out in Spilamberto (Province of Modena, 44°32’00.5” N 11°01’25.3” E), on 18th July 2017. Laboratory measurement have been performed on leaves harvested on the same day, from the same plants. A *Lolium perenne* covered area has been tested successively through a Kipp&Zonen pyranometer on a 4 m^2 area at the Department of Engineering “Enzo Ferrari” (Modena, 44.628529, 10.948436), according to ASTM E1918.

Albedo data achieved through on-field measurements on *Stachys b.* and *Lolium p.* have subsequently been compared with data collected from earth observation satellite Landsat, which largely contributes to monitoring and extracting information on urban areas at high and very high resolutions. The analyzed satellite image comes from WorldView–3 (Digital Globe, 2018) on an area of 28.3 km^2 including the city of Modena, Northern Italy. The used image (Figure 1) was acquired on 15th March 2016, and the albedo has been calculated with ENVI 5.1 Software. The different types of surface have been then classified with Ecognition software. The data processing has been performed according to instruction by Kuester (2018). More specifically, the use of satellite images requires a preliminary classification work: each pixel has specific characteristics that define it into a specific area, called *object*, that has homogeneous properties. The *software* Ecognition Developer 9.1, whose license is provided by Trimble, is applied in order to classify the different objects of the image. The albedo of each object has been thus calculated according to the simplified method proposed by Akdim et al., (2014). The equation introduces below solar reflectance values of the surfaces, with atmospheric corrections:

$$\rho_{sol} = \sum_{\Delta\lambda} w_{\lambda} r_{\lambda} \tag{2}$$

where $r_{\ddot{e}}$ represents the spectral reflectance and $w_{\ddot{e}}$ is the adjustment coefficient for each band, calculated as the ratio of solar spectral irradiance for one band ($I_{\Delta\lambda}$) and the sum of all irradiance values of all bands:

$$w_{\lambda} = \frac{I_{\Delta\lambda}}{\sum_{\Delta\lambda} I_{\Delta\lambda}} \tag{3}$$

The data of $I_{\Delta\lambda}$ have been deduced from the work by Kuester (2018).

Results

The values of solar reflectance measured on *Stachys b*. through the three different test methods are shown in Table 1. At least 3 repeated measurements have been performed for each method in order to achieve a representative standard deviation (SD). The UV-Vis-NIR reflectivity spectrum of *Stachys b.*'s leaf is reported in Figure 2. The measurements with the dual pyranometer according to ASTM E1918A are intended for use when the sun angle to the normal from a surface is less than 45°; this has been verified according to the day of the year and the time of measurements.

Table 1: Solar reflectance $\tilde{n}_{sol}$ of *Stachys b.* measured on the leaf surface according to ASTM E903 (UV-Vis-NIR spectrometer) and ASTM C1549-14 (solar reflectometer), and on the upper surface of the plant canopy layer according to ASTM E1918A (dual pyranometer). Standard Deviation is shown.

Standard Methods	δ_{sol}	SD
E903	0.390	0.009
C1549	0.422	0.004
E1918	0.410	0.005

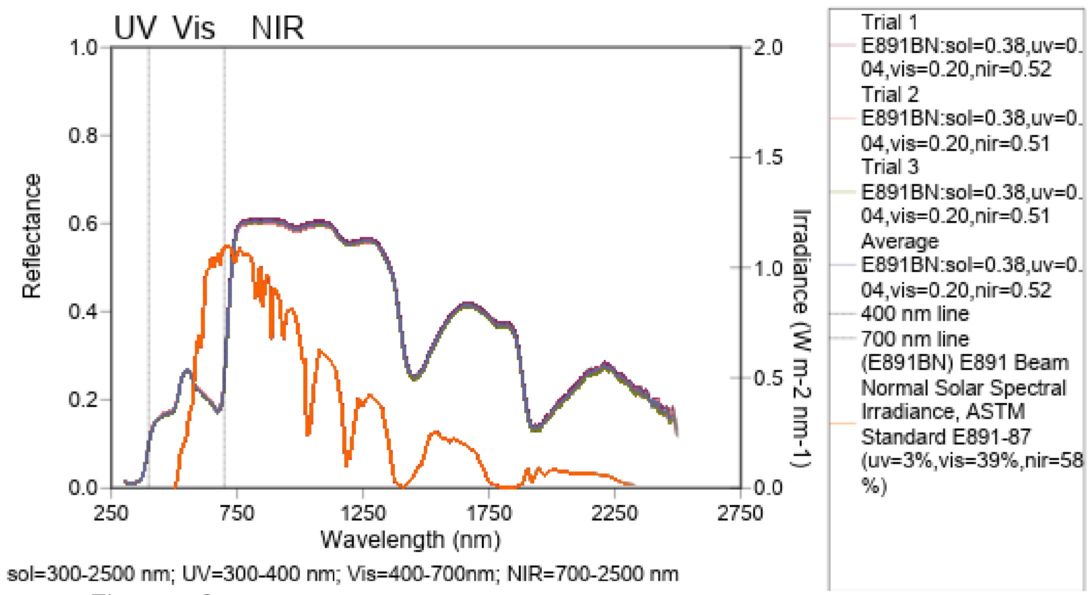

Figure 2: Solar reflectance of a *Stachys b*. leaf: UV-Vis-NIR spectral reflectivity (violet line, scale on the left) and E891BN standard spectrum of solar irradiance (orange line, scale on the right).

ASTM E1918 and its modification dubbed E1918A provide the reflectance value that is relevant in the energy balance of the city surface. The albedo of the single leaf measured by a reflectometer is slightly higher and can overestimate that of the canopy layer, therefore measurements made by albedometers should be preferred for the grass campy of on ground and on roof urban greenery.

Applying the software Ecognition Developer 9.1, through the algorithm “assign class”, different objects have been recognized as streets, buildings, parking and green areas. The algorithm takes in consideration the spectral features to divide the object in different classes. The identified classes in the urban area of Modena are: parking, streets, cool grey roofs, dark grey roofs, red roofs, green areas and other not identified (N.I.) surfaces. The total urban surface covered by vegetation has been calculated and reported in Figure 3, divided in three different “green types”. They involve “Green to natural evolution”, that includes urban forestation and the environmental recovery areas; “Service green”, which includes public parks and residential green areas, and “Others”, as the areas not detectable as one in the first two types. This is equivalent to 7.63 km^2 over the 28,3 km^2 examined. Applying equations (2) and (3), the mean albedo of each type of urban areas of Modena has been calculated and it is shown in Table 2.

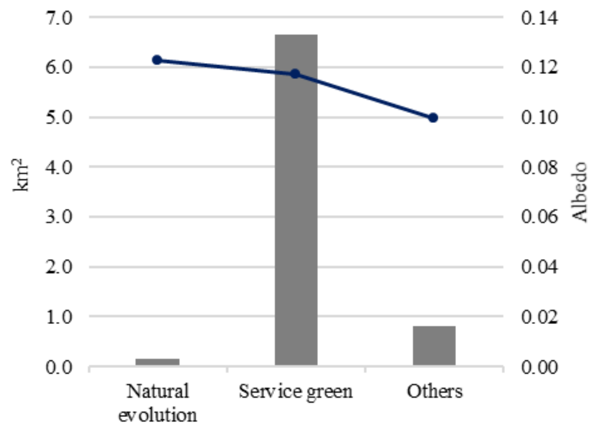

Figure 3: Green areas type and dimensions classified in "Natural evolution"; "Service Green" and "Others". Albedo (δ_{sol}) values from satellite data are reported for each area type.

Table 2: Mean solar reflectance values of different surface types: parking/streets, cool grey roofs, dark grey roofs, red roofs, green areas, and unidentified surfaces. Landsat satellite data are exploited.

Object type	δ_{sol}
Parking-streets	0.126
cool grey roofs	0.268
dark grey roofs	0.148
red roofs	0.142
green areas	0.116
N.I.	0.123

The average albedo δ_{sol} over the whole city has been evaluated to be 0.130. Focusing on the green areas, the mean satellite data return δ_{sol} equal to 0.116. A comparison was made between the albedo calculated from satellite data and that measured on ground in the green area of the Department of Engineering "Enzo Ferrari", covered with *Lolium perenne* sp., according to the ASTM E1918 test method. Values of 0.210 and 0.203 were measured, respectively. Since the variance is less than 0.01, the deviation between the two methods could be considered as irrelevant.

Discussion

The elaboration of WorldView-3 data provided a measure of the surface of public vegetated areas in Modena, which is equal 2.44 km^2. The fraction of this area that can potentially be replaced with high solar reflectance plants such as *Stachys b.* regards 50% of "Service green" zone. This deemed area doesn't contain surfaces covered by trees, as well as other green elements that cannot be replaced with herbaceous plants.

The albedo values recorded on *Stachys b.* according to E1918A modification of ASTM E1918 can allow a non-negligible increase of the albedo of urban green areas. Currently, a typical green surface covered with *Lolium perenne* has an albedo of 0.203, whereas that measured on the canopy layer of *Stachys b.* is as high as 0.410. This value has been used to estimate the average albedo on the green areas of Modena (Figure 4), then the mean improvements in term of microclimate temperature on green zones. A non-negligible improvements of the average albedo were calculated. More specifically, assuming to replace 50% of the existing green areas with plants like *Stachys b*., the albedo onto these areas would increase from 0.116 to 0.237. According to studies by Santamouris(2017), who reported a temperature decrease of urban area up to 1.5 K per 0.2 increase of the average albedo, the widespread adoption of high reflectance greenery can be extrapolated in a temperature decrease of 0.9 K. This value can be added to the potential temperature drop in the close surrounding of green areas due to evapotranspiration as described by several authors (Jonsson 2004; Ellis et al. 2017; Skoulika et al. 2013; Taha. 2015a), which can extend over a 1 km wide area and can range from 1 to 3.5 K (Ellis et al. 2017). With regard to this, the previously estimated 0.9 K temperature drop represents a further cooling potential that high albedo green areas may play on the microclimate of local urban areas.

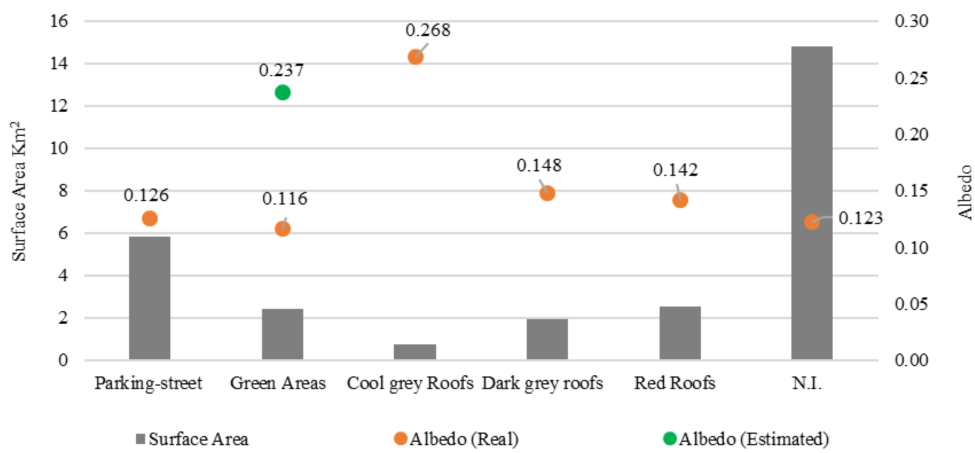

Figure 4: Whole surface area of Modena split in different kinds of surface: Parking-street; Green areas; Cool grey roofs; Dark grey roofs; Red roofs and Not identified (mixed) areas. The satellite data of albedo are reported for each surface type. The estimated albedo calculated replacing 50% of Green areas with *Stachys b.* is reported with the green dot.

The implementation of a higher albedo is not the only important factor involved in countering the heat island by means by plants like *Stachys b*. Its stomatal conductance, indeed, relates plant water use with surface temperature, then with the urban cooling potential (Kala et al. 2016)]. The phenomenon is due to the significant amount of solar heat that is dissipated by vaporization of water through the leaf stomata. A consequence is the lower surface and air temperatures above the green canopy. During heatwaves and, in general, in the summer period, a higher stomatal conductance can reduce heat transfer to the surfaces (Monterusso et al. 2015). In this regard, a comparison of the performance of albedo and stomatal conductance is made for *Stachys b*. and other high albedo plants such as *Helichrysum italicum* and with others species generally used in greenery infrastructures, well represented by *Sedum spp*. and *Heuchera sp.* (Table 3).

Table 3: Comparison of stomatal conductance (mmol $m^{-2}s^{-1}$) and albedo values for possible plant specie suitable to green roof or/and green areas.

Specie	Albedo (δ_{sol})	Stomatal conductance (mmol $m^{-2}s^{-1}$)
Sedum sp.	0.19 (Vaz Monteiro et al. 2017)	110.0 (Vaz Monteiro et al. 2017, Blanusa et al. 2013)
Stachys b.	0.410 (this work)	233.1 (Vaz Monteiro et al. 2017, Blanusa et al. 2013]
Helichrysum italicum	0.440 (Pisello et al. 2016)	n.a.
Heuchera sp.	0.140 (Vaz Monteiro et al. 2017)	200 (Vaz Monteiro et al. 2017)

Conclusions

Urban greenery represents a natural solution to counter the urban heat island effect. Because of the huge variability of available plants species, a deep knowledge on their cooling potential is needed according with their specie-specific morphological and physiological features. This study has investigated the radiative thermal properties of two representative types of urban herbaceous surfaces, *Stachys b*. and *Lolium p*, highlighting their differences in term of albedo. The albedo measured on *Stachys b*. leaves (according to ASTM C1549) and canopy (according to E1918A) is 0.422 and 0.410, respectively. Since the current average albedo measured on green areas of the city of Modena from Earth observation by satellite Landsat data is as low as 0.116, the potential enhancement provided by *Stachys b*. is considerable. Thereby, this work has underlined the importance of a specific and careful selection of plant species to be applied to green areas, particularly herbaceous ones. The replacement of 50% of current urban green surfaces with high albedo plant (*Stachys b*. in this case) could allow an additional decrease of temperature of 0.9 K. Further studies are needed to enlarge the set of high albedo species and understand their cooling potential, thus their contribute against UHI and hot waves in the urban climate.

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