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PM10 Concentration Levels in the Żywiec Basin vs. Variable Air Temperatures and Thermal Inversion

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ABSTRACT

A number of cities in Poland have been coping with the problem of air pollution levels exceeding the allowable limits, with PM10 airborne particulate considered one of the most hazardous factors for human health. Poland ranks high among European countries with some of the highest levels of airborne particulate pollution, and the Polish cities regularly place high in the EU ranking of those with the highest PM levels (and benzo(a)pyrene, a toxic airborne polycyclic aromatic hydrocarbons, or PAHs). Airborne PM10 concentration levels greatly depend on the prevailing atmospheric and topographic conditions. Temperature inversion represents one of the unfavorable weather conditions and this article attempts to study the effect of thermal conditions prevailing in the Żywiec Basin on airborne PM10 particulate concentrations in immissions. The 2016–2021 winter (heating) seasons were analyzed for pollution emissions, especially those related to heating by the municipal sector and classified as "low emissions", i.e. emissions from sources not higher than 40 meters. An analysis of the 2016–2021 heating seasons showed the air temperature exerted a significant effect on combustion processes (low emissions) within the Żywiec Basin. The difference between airborne PM10 particulate levels in immissions at temperatures both above and below zero ranged from 86 μg/m^3 in the 2016–2017 heating season to 25 μg/m^3 in the same period in 2020–2021. Average airborne PM10 particulate concentrations throughout the entire period analyzed stood at 41.3 μg/m^3 for the typical temperature distribution in the elevation profile, whereas inversion almost doubled it (72.2 μg/m^3).

Keywords: airborne particulate, PM10, temperature inversion, low emission.

INTRODUCTION

A report prepared by the European Environment Agency claims that the pollution by airborne PM10 and PM2.5 particulates, tropospheric ozone (O_3) and nitrogen dioxide (NO_2) is the most dangerous issue for the sanitary condition of air in terms of the general composition of the atmosphere together with any admixtures in a given place and time. Almost half a million deaths a year are attributed to airborne emissions, of which Poland reports more than 47 thousand annually [EEA, 2018].

Airborne pollution not only poses a significant threat to human health, but it lowers the standard of living conditions for populations in cities and industrial areas [EEA, 2015]. Among inhaled pollutants, airborne particulate matter (PM) [Kim et al., 2015], especially one with a diameter smaller than 10 μm (PM10) [Lu et al., 2019], ranks among the most hazardous. Airborne particulate is defined as a mixture of both solid and liquid substances, organic and inorganic generated by anthropogenic and natural sources, with an aerodynamic diameter between 0.001–100 μm.

Particles with such small diameters (PM10) easily penetrate the human upper respiratory tract and lungs, causing shortness of breath and coughing, as well as exacerbate any allergy symptoms. However, their effect on the human health may have much more severe consequences if their surface has absorbed toxic substances [Degórska, 2016; Pascal et al., 2013]. Poland ranks high among the countries with the highest PM levels in Europe [EEA, 2018], whereas Polish cities and towns lead in the ranking of EU cities with the highest PM concentration levels (and benzo(a) pyrene, a toxic airborne polycyclic aromatic hydrocarbons, or PAHs) in air [EEA, 2018].

Most air pollution in Poland comes from the housing and municipal sector (home and apartment heating), and road transportation [GIOŚ, 2017] which contribute the so-called low emissions (less than 40 meters high) and generate smog.

Many Polish cities and towns exceed the allowable pollution levels every year [Adamek, Ziernicka, 2017; Pasela et al., 2017]. Airborne PM10 levels are largely attributable to the prevailing weather conditions. High PM10 concentrations depend on the air temperature, wind speeds, directions of the air mass movements and precipitation [Czernecki et al., 2016; Rawicki, 2014; Jędruszkiewicz et al., 2016; Jędruszkiewicz et al., 2017; Gioda, 2013]. The lower the temperature and the slower the wind – the higher the airborne particulate concentrations are [Chlebowska-Styś, Sówka, 2015]. High pressure systems squeeze the mixing ground level lower causing higher particulate concentrations. Conversely, lower PM10 airborne particulate concentrations are observed at times of precipitation [Ćwiek, Majewski, 2015; Oleniacz et al., 2014].

Air temperature inversion, also known as thermal inversion, consists in air temperature rising with the altitude, a situation unlike the typical one when – in line with adiabatic changes – rising air masses expand, i.e. lose the internal energy of the system trying to counteract the external atmospheric pressure [Grajek, Szyga-Pluta, 2021]. A number of scientific papers correlate the thermal inversion issue with impaired dispersion of air pollutants and fog formation. Rendón et al. (2014), Palarz et al. (2015), Largeron and Staquet (2016), Palarz and Celiński-Mysław (2017) took up the problem of thermal inversion and its occurrence at a time of high pollutant level concentrations. Many authors have also attempted to define the effect of meteorological conditions on the pollution levels [Kalbarczyk et al., 2018; Czarnecka, Niedzgorska-Lencewicz, 2017; Palarz, 2014; Bokwa, 2012; Majewski et al., 2018; Dacewicz et al., 2019; Palarz, 2017; Czernecki et al., 2016; Rawicki, 2014; Jędruszkiewicz et al., 2016; Jędruszkiewicz et al., 2017].

INVESTIGATION SCOPE AND METHODOLOGY

The Żywiec Basin is a large, triangular, mountainous basin in the Western Beskidy range with its center close to where two Soła river tributaries empty into the larger river: the Koszarawa on the right side and the Żylica on the left.

According to the scientific regionalization of Poland developed by Jerzy Kondracki, the Żywiec Basin borders the Silesian Beskid to the west and Silesian Foothills to the north (connecting through the Wilkowicka Brama [Gate] and Little Beskid; whereas from the south east and south – it borders Makowski Beskid and Beskid Żywiecki (Figure 1). The valley bottom at an elevation of 340 to 500 m ASL stretches for roughly 20 km west to east and for approximately 15 km north – south covering about 320 sq kms. Figure 2 presents a schematic profile of the Żywiec Basin.

Air temperature measurements used in the conducted analyses were provided by two weather stations of the National Research Institute of Meteorology and Water Management: Radziechowy (385 m ASL) representing the Żywiec Basin bottom, and Pilsko Mt. (1557 m ASL) representing the Beskid Żywiecki uplands. The altitude profile (Figure 2) allowed researchers to evaluate the air temperature differences used for investigating the thermal inversion phenomenon in the Żywiec Basin. The meteorological data came from the NRIMWM archives as operating data recorded at hourly time intervals.

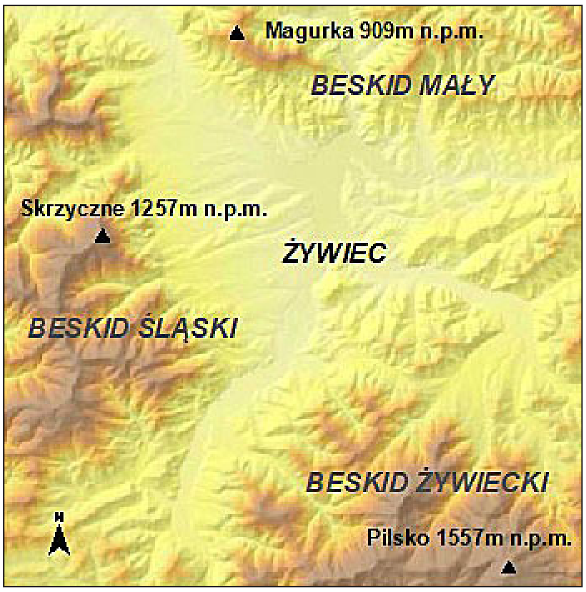

Figure 1. Geography and research area location

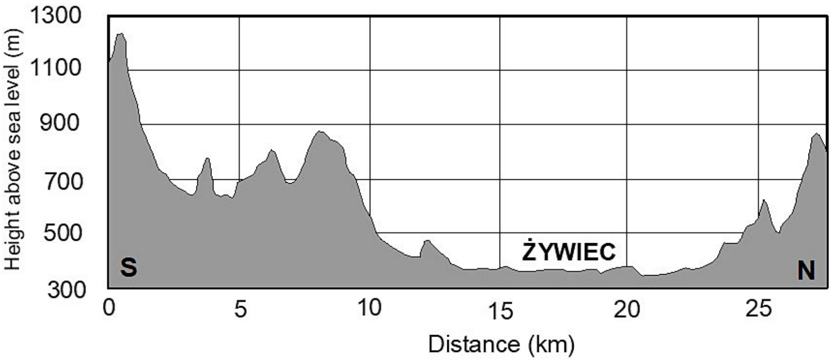

Figure 2. Location of the air monitoring station in the south-north profile of the Żywiec Basin

RESEARCH RESULTS

Average PM10 concentrations amounted to 57.9 µg/m^3 in the five heating seasons analyzed, with the highest one observed in the winters of 2016–2017 (78.5 µg/m^3). Thereafter, concentrations dropped in subsequent seasons, reaching 40.6 µg/m ^{3} in the 2019–2020 season; however, the following heating season saw the average PM10 concentration rise to 52.9 µg/m ^{3} again (Figure 3).

An analysis of the average airborne PM10 concentration in selected months of the winter seasons shows the highest values were recorded in the following months: January (141 µg/m^3) and February (110.0 µg/m^3) of the 2016–2017 winter. High concentrations were also recorded in February of the 2017–2018 season (97.9 µg/m^3) (Table 1).

The number of days with permissible PM10 concentrations exceeding the daily allowable levels D$_{24}$ provides a reliable indicator. In the analyzed seasons, the number of such cases ranged from 90 days in the 2016–2017 season to 53 days in the 2019–2020 one (Figure 4).

The air temperature in the heating seasons analyzed varied both seasonally (Figure 5) and from

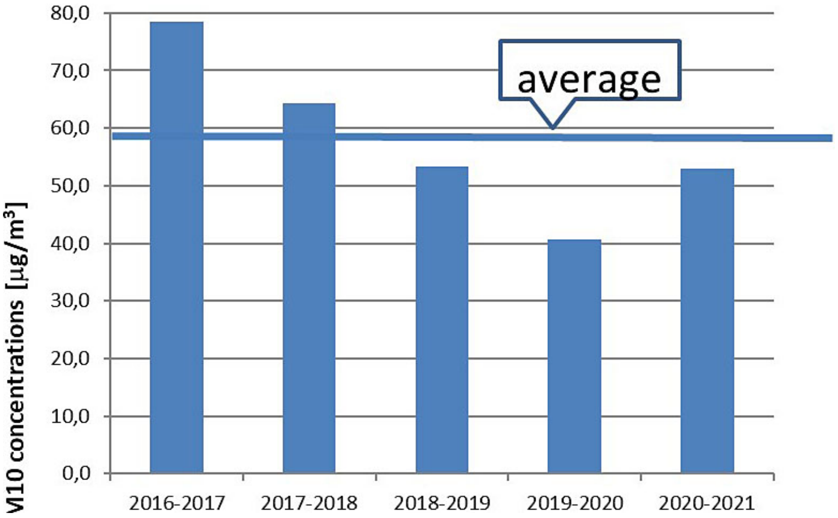

Figure 3. Average atmospheric PM10 concentrations in 2016–2021 winter seasons

Table 1. Average monthly PM10 concentrations in µg/m ^{3} in 2016–2021 heating seasons

Winter	Average PM10 concentration [µg/m^3]					
	X	XI	XII	I	II	III
2016–2017	39.1	47.5	83.1	141.4	110.0	49.7
2017–2018	31.5	57.9	48.5	58.5	97.9	91.3
2018–2019	44.9	71.8	45.0	64.8	55.4	37.5
2019–2020	33.2	46.6	40.6	57.1	26.5	39.7
2020–2021	26.2	46.6	64.0	61.5	68.8	50.3

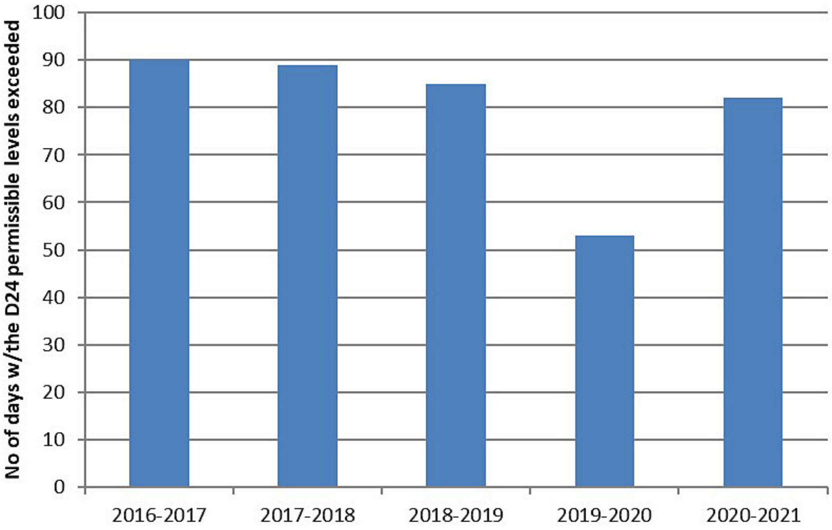

Figure 4. Number of days with the D_{24} permissible level exceeded in 2016–2021 heating seasons

month to month (Table 3). The average winter air temperature in the analyzed periods ranged from 1.9 °C in the 2016–2017 season to 5.0 °C in the 2019–2020 season.

An analysis of the number of days with the permissible level of airborne PM10 concentrations exceeded, and especially the analyzed air temperature, does not show any specific trend (Table 2) since a large number of such cases have been observed both in November (22 days in the 2018–2019 season and in January – February (23 days in the 2016–2018 seasons).

The air temperature in the heating seasons under consideration varied both when calculated in terms of seasonal average (Figure 5) and month-by-month (Table 3). In the analyzed time periods, the average air temperature for the winter season ranged from 1.9 °C in the 2016–2017 season to

Table 2. Number of days with the PM10 daily standard D_{24} exceeded

Winter season	Number of days with PM10 standard exceeded					
	X	XI	XII	I	II	III
2016–2017	9	9	17	23	18	14
2017–2018	5	17	11	14	23	19
2018–2019	11	22	11	13	18	10
2019–2020	6	10	10	15	3	9
2020–2021	1	12	17	17	18	17

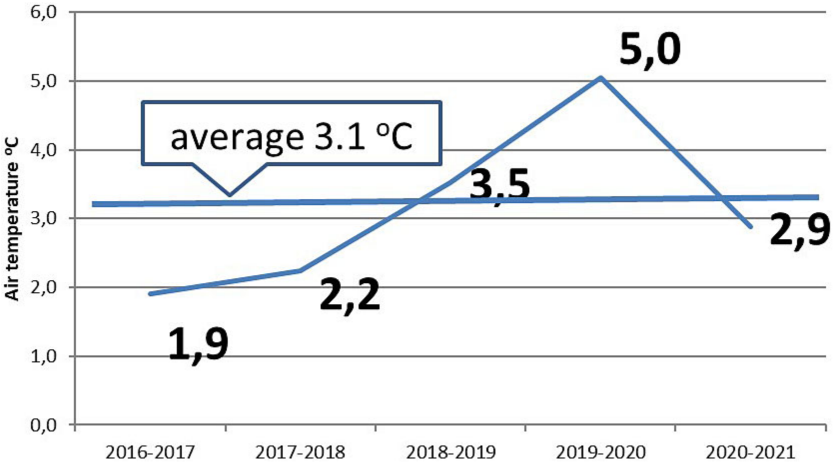

Figure 5. Average air temperatures in 2016–2021 heating seasons

5.0 °C in the 2019–2020 season. Comparing the variability of the air temperature in the analyzed years (Figure 5) with the PM10 concentration levels (Figure 3), one will observe the effect of the thermal conditions on the airborne PM10 concentrations; the fact resulting from burning fuels for heating (low emissions).

An analysis of the effect of air temperatures on higher emission activity, and thus the observed increase in airborne PM10 concentrations (immission), is presented seasonally (Figure 6).

Average monthly PM10 concentrations also point to a considerable effect of air temperatures on the airborne PM10 particulate concentrations, and thus the observed levels of PM10 concentrations in immissions (Tables 3–4).

The relationship between airborne PM10 concentrations and the air temperature points to a strong statistical relationship at the R2 level exceeding 50% of the explanations (Fig. 7).

A 24-hour and hourly analysis of the relationship failed to show any such dependence, since the pollution concentrations in the Żywiec Basin are also affected by thermal inversion which even on warmer days results in high airborne PM10 concentrations. To this end, an analysis of the frequency of its occurrence in the heating seasons under consideration and its effect on airborne PM10 concentration levels was carried out.

The Żywiec Basin covers an area where topoclimatic conditions favor formation of thermal inversion and when such a phenomenon was observed in the middle of the observation period (Table 5). Nevertheless, no material regularity both with relation to months or seasons was found (Tables 5–6). The synoptic situation – occurring but ignored at the time of preparing this paper – will play a decisive role here.

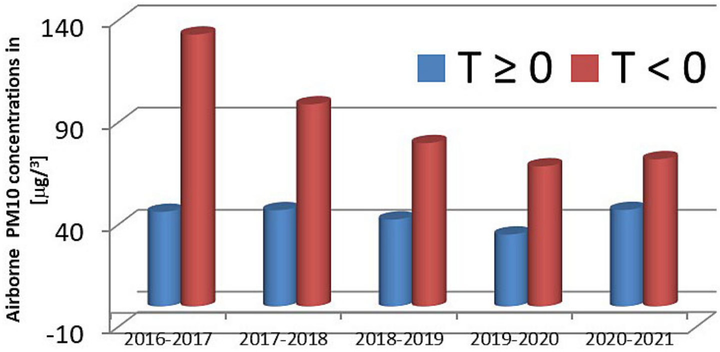

Figure 6. Average PM10 concentrations at temperatures above 0 °C (T>0 °C) and below 0 °C (T<0 °C) in 2016–2021 winter seasons

Table 3. Average monthly PM10 concentrations for positive temperatures in 2016–2021 heating seasons

Winter season	Average monthly PM10 concentrations [µg/m^3]					
	X	XI	XII	I	II	III
2016–2017	37.8	45.1	39.0	67.2	67.4	43.3
2017–2018	31.5	53.5	31.3	56.7	48.9	68.2
2018–2019	44.9	65.9	28.2	22.7	47.4	35.4
2019–2020	29.9	44.3	36.4	41.4	23.0	37.0
2020–2021	26.3	42.1	42.5	65.7	57.7	48.9

Table 4. Average monthly PM10 concentrations for negative temperatures in 2016–2021 heating seasons 2016–2021

Winter season	Average monthly PM10 concentrations [µg/m^3]					
	X	XI	XII	I	II	III
2016–2017	78.6	54.1	116.5	157.0	169.4	104.7
2017–2018	34.0	111.1	82.2	61.8	105.8	122.9
2018–2019	42.2	83.7	76.8	83.7	75.5	67.2
2019–2020	93.7	100.5	53.2	94.7	54.4	48.2
2020–2021	51.2	69.2	96.4	58.0	83.7	52.7

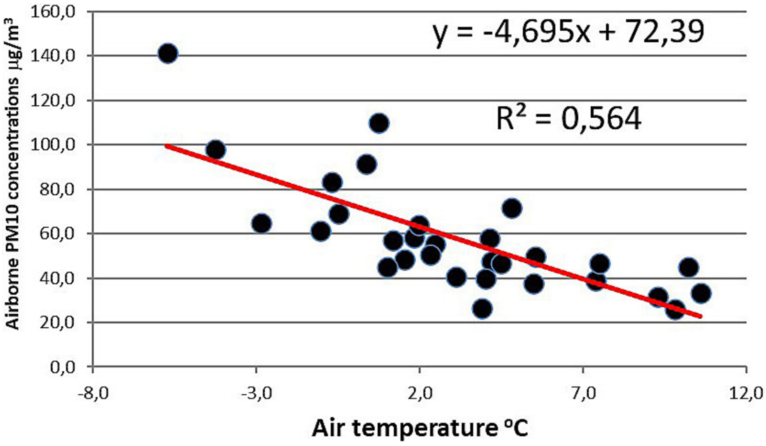

Figure 7. The relationship between airborne PM10 concentrations and temperature, by month

Table 5. Number of days with thermal inversion in individual 2016–2021 heating seasons

Winter season	Number of days with thermal inversion						
	X	XI	XII	I	II	III	Total
2016–2017	8	6	15	19	14	10	72
2017–2018	11	9	6	7	8	12	53
2018–2019	18	20	2	5	15	6	66
2019–2020	15	14	9	17	2	10	67
2020–2021	12	12	15	7	14	6	66

Table 6. Thermal inversion duration in individual 2016–2021 heating seasons

Winter season	Number of days with thermal inversion [hours]						
	X	XI	XII	I	II	III	Total
2016–2017	49	29	206	241	188	58	771
2017–2018	89	69	27	52	59	89	385
2018–2019	198	228	30	43	98	40	637
2019–2020	150	105	74	164	10	70	573
2020–2021	52	178	237	36	155	52	710

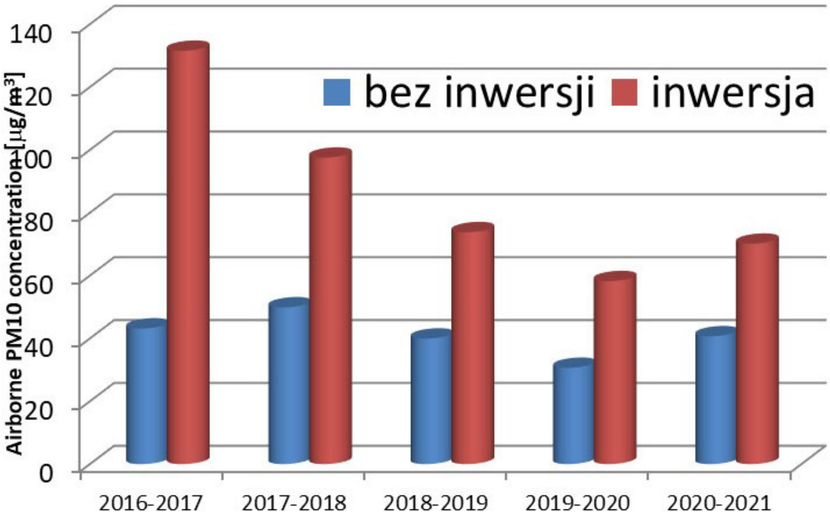

Figure 8. Average airborne PM10 concentration occurring during and without accompanying inversion (Legend: 🟦 no inversion 🟥 inversion)

Table 7. Average airborne PM10 concentrations in a period without inversion

Winter season	Average PM10 concentration [μg/m^3]					
	X	XI	XII	I	II	III
2016–2017	35.7	41.6	47.3	48.6	49.5	42.6
2017–2018	22.5	43.7	42.8	49.9	87.1	55.5
2018–2019	32.0	51.5	40.6	48.6	33.9	32.8
2019–2020	22.9	31.4	42.3	36.4	24.3	28.0
2020–2021	23.9	39.4	26.5	47.8	53.4	49.6

Table 8. Average airborne PM10 concentrations in periods with inversion

Winter season	Average monthly PM10 concentrations [μg/m^3]					
	X	XI	XII	I	II	III
2016–2017	48.8	71.0	121.2	200.1	170.5	64.6
2017–2018	47.8	91.3	72.0	87.8	124.9	147.9
2018–2019	53.1	79.4	86.2	149.1	71.5	57.0
2019–2020	44.1	64.0	36.3	74.1	56.5	64.4
2020–2021	29.8	55.9	91.1	108.4	80.4	52.9

The phenomenon has a vital effect, in line with the general aerosanitary knowledge, upon pollution concentrations, especially when taking river and mountain valleys into account. Therefore, airborne PM10 concentrations were tabulated, including periods of thermal inversion (Figure 8).

CONCLUSION

When analyzing the 2016–2021 heating seasons, a significant effect of the thermal conditions (air temperature) upon combustion processes (low emission) was observed in the Żywiec Basin. The difference in the average airborne PM10 particulate concentrations at both positive and negative temperatures ranged from 86 μg/m^3 in the 2016–2017 heating season to 25 μg/m^3 in the 2020–2021 heating season. The PM10 concentration increase also confirms a significant statistical dependence of 56% on dropping air temperatures.

The frequent inversions observed for approximately 65 days in a heating season favor PM10 particulate concentrations in the Żywiec Basin. The average concentrations of airborne PM10 particulate over the entire period analyzed and for typical temperature – elevation distribution amounted to 41.3 μg/m^3, whereas with an accompanying inversion, the concentrations rose almost twice as much (72.2 μg/m^3).

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