Review of Coal Gangue Characteristics and Ecological Restoration Management Technology

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Abstract. Coal gangue has become one of the industrial wastes with the largest annual discharge and accumulated stock in China. The disorderly accumulation of coal gangue not only occupies a large amount of land resources and causes natural disasters, but also pollutes the surrounding ecological environment, which in turn affects human health and normal production and life. In this paper, the physical, chemical and pollution characteristics of coal gangue are summarized, and the ecological restoration mode is divided into two modes: traditional "end treatment" and "treatment while piling". The action mechanism, advantages and disadvantages and application scope of various ecological restoration technologies involved in the two modes are listed, compared and analyzed, which provides scientific reference for the restoration and treatment of other similar geological environments.

1. Introduction
Coal gangue is the fixed product during the process of coal mining, washing and processing. And its chemical composition is SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MgO, CaO, TiO$_2$, etc. Since the middle of the 20th century, coal gangue emissions have been increasing, and now it has become one of the industrial waste that accounts for the highest annual emission as well as that of the stored volume in China. According to statistics, the cumulative stockpile of coal gangue in China has exceeded $6 \times 10^9$ t, and it is still growing at the rate of hundreds of millions of tons per year [1]. Disorderly discharge and accumulation of coal gangue not only occupies a lot of land, but also easily explodes spontaneously, which will pollute the atmosphere, soil and water in the mining and surrounding areas. In the meanwhile, it will damage to the local ecological environment and impact on human health, life as well as production. In this instance, how to deal with and use comprehensively of coal gangue gradually attracted people’s attention. The United States and other developed countries have long been aware of the environmental hazards and other social conflicts caused by coal mining, so the land restoration after mining has been carried out, and relevant laws and regulations have been formulated for enforcement. But the research on the ecological restoration technology of coal gangue in China started late. Due to economic, technical and other reasons, the current domestic mining land reclamation rate is only about 12% [2], which compared with developed countries, the gap is still large. Therefore, it is necessary to continue to strengthen the ecological restoration technology of coal gangue, so as to establish a long-term stable ecosystem and seek a low-cost and high-efficiency ecological restoration pathway.

This paper mainly outlines the physical, chemical and pollution characteristics of coal gangue, and analyzes various types of gangue ecological restoration technology at home and abroad nowadays.
2. Characteristics of Coal Gangue

Weathered products on the surface are an important part of the coal gangue pile soil, and its characteristics have great differences from those of the ordinary terrestrial soil. The current study on the characteristics of gangue is mainly to analyze the physical and chemical properties of weathering and pollution characteristics to determine whether it is suitable for vegetation growth, and to provide scientific basis and guidance for gangue filling reclamation project and mine ecological restoration technology.

2.1. Physical Characteristics

From the spatial dimension, the surface of coal gangue can be divided into different layers according to the different degrees of weathering. Meanwhile, the physical properties such as particle size, thickness, color and water retention properties are not exactly the same between layers. Gao [3] divided the surface profile of the gangue pile into three parts: weathered layer (0-10 cm), weakly weathered layer (10-30 cm) and unweathered layer (>30 cm). The weathered products on the surface of the gangue pile mostly have a blocky and gravelly structure (64%~96%), and the content of fine grains below sand grains (<5 mm) only accounts for about 2%~14 %. Cai, et al [4] studied the relationship between gangue particle size and water retention performance. The results showed that the characteristics of gangue particle size distribution have a significant effect on its water retention, and gangue with particle size below 2 mm is essential to improve the water retention of gangue. Stewart [5] studied the water retention of weathering which is different ages, and determined its water tension in the range of 10~1500 J/kg. The surface weathering of coal gangue has coarse particles, poor topsoil structure, low water holding and water supply performance, and poor moisture retention performance.

In terms of time dimension, the above-mentioned properties of its various layers change at different rates as the stacking time is prolonged and the weathering years increase. The results of Zheng's study on the changes of physical and chemical properties in the natural weathering process of coal gangue in Fuxin mining area found that with the increase of the years of stopping gangue discharge, the thickness of each weathering layer increases, the color deepens, and the speed of change increases first and then decreases, with the most rapid in the middle period [2].

2.2. Chemical Characteristics

The composition of coal gangue is more complex, and its main minerals include clay minerals, carbonate minerals, bauxite, pyrite, quartz, mica, feldspar, carbonaceous and plant fossils. Zheng, et al. [6] analyzed the composition of macronutrients in the gangue weathering and soil particulate matter by energy spectrum. He found that they are basically the same, that is, C, O, Al, Si, and a small amount of Mg, K, Fe as well as other elements, but the mass fraction of element C in the gangue particulate matter is 3.3 times of the control soil, and the total organic carbon content in the gangue weathering is negatively correlated with the weathering degree of the gangue weathering. For trace elements, most of the relevant research on the harmful Hg, Ge, Cr, Pb, Cu, As, Zn and other heavy metal elements were measured. It is found that the contents of the same elements in coal gangue from different mining areas vary greatly; not all gangue will appear the phenomenon that heavy metal exceed the standard; the same gangue sample did not detect all elements at the same time exceed the standard; Hg, As, Zn, Cd are the elements that exceed the standard rather seriously [7].

Duan [8] studied the salt content of weathering products and found that the total salt content of gangue was similar to that of loess without spontaneous combustion, accounting for only 0.21%, which had no effect on the growth of planted vegetation. Zheng found that with the increase of gangue discharge years, the total amount of N, P, K and total salt in gangue are growing simultaneously; Kimber [9] then studied the pH value of weathering, and the results showed that the potential acidity pH value of unburned gangue weathering is above 4.0, which does not affect the growth of plants, and the pH value of weathering shows an overall decreasing trend.
To sum up, the composition of gangue weathering material is similar to the basic composition of soil, but the proportion of relevant elements is different, and the content of various components of gangue will change accordingly with the change of time.

2.3. Pollution Characteristics

Coal gangue has its unique physical structure, chemical characteristics and gangue piling, which has caused different degrees of pollution and damage to the ecological environment of the mine.

Gangue pile structure is loose, unstable, and very easy to cause collapse, landslides and other natural disasters; The voidage between coal gangue is large, and its surface is in full contact with air, the carbon minerals and sulfur iron ore (the main component of FeS₂) in gangue is oxidized by air. And then being dissolved in water to form sulfuric acid aqueous solution. This process exothermic promotion of coal hydrolysis, while the temperature of the gangue pile internal is rising. When the temperature reaches the combustion point of coal, it can ignite the coal in the gangue and promote the combustion of carbonaceous substances in the coal, so that cause the gangue pile spontaneous combustion to release the SO₂, CO, H₂S, NO, C₉H₈ and dibenzanthracene and other polycyclic aromatic hydrocarbons, etc. which seriously pollute the atmosphere of the mine, and cause different degrees of harm to the human respiratory system [10].

After gangue pile internal self-ignition, if its heat production rate is always higher than the rate of heat dissipation, gangue will continue to burn, and to release the SO₂. The gas fills in the internal self-ignition area, and the temperature rises to more than 800 ℃, thus forming a high temperature and high pressure internal environment. When its internal temperature and pressure reach a certain value, the explosion will be triggered according to the thermodynamic principle [11]. As a common geological disaster in China's coal mines, gangue pile explosions have caused many casualties.

Coal gangue produces acidic wastewater under the effect of long-term weathering and rainwater drenching, which is characterized by low pH, high sulfate concentration and the presence of heavy metal elements in soluble state. When it forms surface runoff into the surface or underground, it will cause pollution of soil, surface water or groundwater. Zhang, etc. [12] measured that the concentrations of four major pollutants SO₄²⁻, NO₃⁻, Fe and Cu in surface water around the abandoned site of Dahe coal mine in Guizhou were as high as 869.45 mg/L, 35.16 mg/L, 26.06 mg/L and 40.85 mg/L, respectively, during the high flow period/the flood period, which have far exceeded the national environmental quality standards for surface water. Due to the migration of water, the pollution will also be continuously expanded to the surrounding area. When people drink the contaminated groundwater, the heavy metals and other harmful substances in it will seriously endanger human health and even life. Chen, et al. [13] showed that Cd, Cr, Pb and Cu are the most serious heavy metals polluted in the soil around the abandoned gangue pile. In the long-term leaching process, several elements continuously migrate to the surrounding soil to enrich, changing the original structure and function of the soil.

3. Ecological Restoration Technology of Coal Gangue Pile

The ecological environment of coal gangue pile has been damaged to different degrees, often beyond the self-regulating ability of the ecosystem, which requires human intervention and restoration. For the concept of ecological restoration, some scholars in China defined it as reconstruction of damaged or degraded ecosystems, so that they restore the original structure as well as function and achieve the process of system self-sustaining state [14] [15]. With the support of national policies and the progress of science and technology, various ecological restoration methods have become increasingly mature. Nowadays, domestic and foreign ecological restoration models are generally divided into two categories: one is the traditional "end-of-pipe treatment", and the other is the dynamic treatment model that advocates "healing while piling". The specific technologies involved in the two macro restoration models are divided into plastic land preparation technology and vegetation cover technology in order of priority.
3.1. Ecological Restoration Model

3.1.1. "End-of-pipe treatment" restoration model. In a longer period of time, the domestic and foreign restoration model is the traditional "end management" approach. Mine emissions, sales and subsequent restoration has a strict time sequence, each link in turn, that is, "first emissions, after restoration". Although the repair program can make the gangue yard environment have been greatly improved after management. Due to the repair is not timely, with the gangue pile time growth, the disadvantages of this way then emerged: a. Three-dimensional structure of the gangue pile is not stable, and is very easy to cause the mountain collapse; b. angue pile is more loose, with gaps and holes, and is very easy to cause oxidation spontaneous combustion phenomenon, increasing the difficulty of subsequent management.

3.1.2. Treating while heaping dynamic management model. Unlike the traditional "end-of-pipe treatment", treating while heaping is based on the concept of "source and process control" [16], and its core purpose is to pursue "effectiveness" and timely restoration of the damaged ecological environment, to alleviate the contradiction between the development and utilization of coal resource and environmental protection, and ensure the development of mining activities in a green, circular and sustainable direction.

Wei [15] proposed that we can plan out the gangue discharge, sales and dynamic reclamation of several areas in space for production mines whose production, sales, reclamation are at the same time. As for the part that cannot be sold out in time can be planned out for reclamation. The gangue storage and transportation can be constructed in the gangue road outside, and the gangue discharge, temporary storage, loading, unloading, transfer and other links can be conducted in this storage and transportation. If not timely marketing, they will be transported back by the gangue road to the collapse pit for backfill reclamation, through the orderly stacking of layers, covering loess and alkaline substances and other barrier layer, blocking the gangue pile inside and outside the air flow cycle, to be stacked to the boundary after the unified vegetation recovery. The advantages of the program are: a. Providing a variety of ways for coal gangue treatment, to meet the mine gangue discharge, export and environmental protection and other needs. When the investment amount is moderate, it can achieve social and economic benefits of the win-win; b. Constructing the closed storage and transportation space, to be conducive to the subsequent gangue discharge project and to reduce the pollution of the environment of open-air operations; c. Process control.

3.2. Ecological Restoration Technology

3.2.1. Shaping and preparation techniques. Shaping and preparation refers to the principle of land use, the digging loss, collapse, pressure occupation of the land to take appropriate reconstructive technology process, and apply engineering theory and physical, chemical, biological, ecological technology to reconstruct a suitable soil profile and soil fertility factors [17] so that to reduce or prevent damage to the ecological environment of the coal gangue pile, and restore the fertility of the land, productivity and ecological balance of the mine activities. Plastic land preparation technology can be subdivided into two categories of mountain shaping and soil improvement technology.

(1) Mountain shaping technology

Gangue mountain generally steep slope, and more than 60% of the gravel or block accumulation. Its structure is loose and unstable. In case of rain and windy weather, the weathering is easy to slip to form runoff and erosion; At the same time gangue between the existence of non-continuous gaps and holes, and air contact reaction prone to spontaneous combustion and other disasters. Therefore, before implementing the greening project, it is necessary to do the shaping treatment on the gangue mountain. Generally, it will be set to conical shape to maintain stability, while building the road around the mountain, leveling the top of the mountain, reshaping the landscape, constructing drainage system, etc.

Su [30] proposed to adjust the slope to below 30°, the slope grading generally 10~15m for one level, and set 2m wide grading horse path. Zhang [18] studied the land preparation and mulching engineering
of the coal gangue dumps in the southern area of Walnut Rock Ditch, and the slope of the side slope after finishing was around 28°; After shaping, the mulch was milled so that the thickness of the platform mulch was 50~100cm and the thickness of the side slope mulch was 30~50cm, and it was manually compacted. This method can effectively block the air from entering the inside of the gangue hill, so as to achieve a certain function of fire retardant. Zhang [29] proposed that Jiangxi Yangquan coal mine gangue field adopts gravity slurry stone gangue dam, the top of the dam is 1m wide, and the side slope is 1:0.5. The side slope above the gangue dam is protected by 1:1.5 cut slope.

(2) Soil improvement technology

By the physical and chemical properties of coal gangue can be known that the coal gangue mountain weathering degree is different in different geographical environment, and the same gangue mountain of different parts also have different degree of weathering. Niu [19] proposed three kinds of reclamation: a. for those well weathered parts, greening them without soil cover. b. For those moderately-weathered parts, greening them will thin cover of soil. c. For those parts being weathered not so good, mulch them with thick soil layer for greening. In comparison, no mulch greening reduces the link of soil transportation, and saves a lot of manpower, material resources, and time. However, because it contains almost no humus, and the effective nitrogen, phosphorus and potassium nutrients are insufficient, and the water as well as fertilizer retention performance is poor, the overall restoration effect of this method is weak. Measures such as water retention and fertilization are needed to improve the soil environment.

For mulch greening, Song, et al. [20] studied the effect of the mulch method on the moisture status. It shows that the soil moisture condition of gangue and the cover of loess mixed is significantly better than that of pure loess covered gangue hill. The gangue mulching pattern with the interval of 0.15~0.25m and the coverage rate of 35%~45% ensures the good seedling rate and the moisture requirement of plant growth, and the vegetation recovery condition is optimal.

For the high acidity of gangue mountain soil, Niu, et al. [19] summarized two kinds of acid treatment methods: sorting and neutralization. The former is in the gangue pile, the gangue in the acid-causing minerals (such as pyrite, etc.) to be sorted and recovered to reduce the acidity. The latter is the use of alkaline chemicals (fly ash, limestone, phosphate powder, etc.) to neutralize the strong acidity of the gangue. Fly ash particles are fine, in the process of mixing with the gangue can fill the large pores between the gangue to prevent the gangue mountain spontaneous combustion. Phosphate powder can improve the pH value and the fertility of the substrate at the same time. By spreading the alkaline chemicals evenly on the gangue hill to fully react, and then tilling 10~15cm. It can enhance the soil fertility and the pH value at the same time. But in the meanwhile, it is noted that when the pH value is too low, the large amount of lime at once is not conducive to plant growth. When the moisture content in the fly ash of the wet drainage method is too high, it can cause spontaneous combustion or even explosion.

For the soils of gangue hills restored with soilless vegetation, there are often high carbon content but almost no humus, and insufficient effective nitrogen, phosphorus as well as potassium nutrients, and poor water and fertilizer retention performance. In this regard, it is pointed out that the use of biological rehabilitation technology to improve the soil is the most mature and feasible [24]. That is, a layer containing common lignite, sawdust, cereal stalks and organic fertilizer of nitrogen, phosphorus and potassium fertilizer with high percentage is sown on the surface of gangue. This new technology can be used in the absence of topsoil layer, and it can make the gangue compound layer into fertile soil only at a growth period. Chen, etc [25] showed that the initial growth of plants without any treatment was increased by 256.1%, 140.8% and 72.7% for cinder fill + fertilizer treatment, fertilizer treatment only and cinder fill treatment only.

For the natural raw soil with low microbial content and poor soil nutrients, microbial reclamation techniques are available for restoration. Hong [26] investigated the microbial amount of gangue mountain in Yangquan three mines and found that the amount of bacteria in gangue was 8.2×104/g, the amount of actinomycetes was 1.6×104/g, and the amount of fungi was 2.08×104/g, which was obviously less than the surrounding loess. It was not conducive to the improvement of plant resistance and the fertility of gangue. Ma [22] conducted experiments for bacterial microbial inoculation, and the results
showed that after inoculation with P-K and N-P bacteria, the acre yield was 266.11, 291.01 and 286.89 kg, respectively. And the yield increase was 8.27% and 9.82%, respectively, which was compared with the control yield of 264.98 kg. It showed that the application of microbial fertilizer significantly increased the crop yield of the reclaimed land. This method can make the soil which lost microbial activity re-establish and restore the microbial system and accelerate the substrate improvement of the soil. Nowadays, there are still few studies on microbial reclamation technology for coal gangue hills at home and abroad. The further research and promotion are needed.

For the phenomenon of large amount of soil and inconvenient transportation in mulching greening, German scholar Arias-Fernandez [21] proposed that using urban sludge rich in N, P, K and organic substances to cover the surface of coal gangue weathering can achieve better reclamation effect. This method can effectively reduce the transportation link of mulching greenery while improving the water and fertilizer retention performance of the surface layer of gangue mountain, while treating waste with waste and reducing the treatment cost of sewage plant. However, it also faces problems such as the subsequent treatment of harmful pathogenic bacteria and clogging of mud delivery pipeline.

For the characteristics of thick gangue, poor soil water content and soil temperature conditions, Lv [23] proposed a water conservation system with water and fertilizer retention capacity. With the help of gravitational potential energy, the system provides sufficient water for plants in the planting area by diverting the stored water in the catchment area to the adjacent planting area from the slope structure. And by covering the seedling hole pits with plastic film to regulate soil temperature, reduce water loss as well as fertilizer loss, and prevent soil slumping.

Table 1. Comparison of Mechanism, Advantages, Disadvantages and Scope of Application of Mountain Improvement Technologies

| Methods                        | Mechanisms                                                                 | Advantages                                                                 | Disadvantages                                                                 | Scope of Application                                      |
|--------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------|-----------------------------------------------------------|
| Sorting and neutralization method | Use physicochemical method to adjust acidity and alkalinity                | treat waste with waste and reduce treatment cost                          | Excessive use of lime and fly ash has a negative effect on the environment   | Gangue Mountain with high sulfur content and more serious acidification |
| Bioremediation technology      | High percentage organic mixture of lignite, sawdust, and common nitrogen, phosphorus and potassium fertilizers are proportionally applied to the surface of gangue weathering materials to enhance fertility | Short action cycle; wide range of application; high yield; realize the recycling of solid waste such as sawdust | Determining the optimal mixing ratio of several substances such as lignite and sawdust is more complicated | Almost no humus, and the effective nutrients are insufficient, and the gangue mountain with poor water and fertilizer retention performance |
| Sludge application method      | Use of urban sludge rich in organic matter, CEC content and soil fertility in mining soils | Reduce the transportation link of mulch greening; reduce the treatment cost of sewage plant and realize the recycling of sludge | Causes accumulation of heavy metals in the soil; subsequent treatment of harmful pathogens; clogging of mud transport pipes | Gangue Mountain with average weathering, low organic matter content, lack of nutrients and poor soil fertility |
| Microbial Reclamation Technology | Inoculation of new plants with microorganisms and endophytic mycorrhizae restores the microbial system to the soil and accelerates soil substrate improvement | Increase the abundance of biological species; help maintain the stability of this ecosystem | Screening of mycorrhizae; limitations in selecting plants for study; operational difficulties | Natural habitats with poor nutrients, poor soil structure, and low microbial content |
| Water Saving System            | Provide sufficient water for plants in the planting area by diverting natural precipitation or watering water from the catchment | High efficiency of water use; mulch can regulate soil temperature; low cost and easy to implement | Large overall construction volume; plastic mulch is difficult to degrade and submerged in the | Gangue thickness is large, soil water content and soil temperature conditions are poor |
By putting planting soil, water retention agent and fertilizer inside the polyester cotton mesh biodegradable vegetation bag, the bag filled with soil is to regulate the soil environment. Vegetation bags can be degraded and reused; vegetation bags are flexible and can withstand a wide range of deformation without breaking. The preparation process of vegetation bags and water retention agents is more complicated; the cost is higher.

For gangue slopes prone to soil erosion, ecological vegetation bag method is often used for slope water as well as soil conservation and greening. The seeds and the mixed soil substrate with water and fertilizer retention capacity are put into the vegetation bag. Regarding the composition of the mixed substrate, Liu, et al. [28] proposed that it is made of planting soil, fly ash, gangue powder, straw, fertilizer and water retention agent, while Lv [23] mixed coconut coir, water retention agent and planting soil in the configuration. The water retention agent is resin-like substance, which can be used repeatedly, and the water release period can reach 40–60d after absorbing water, which can save more than 50% of water and 30% of fertilizer. Coconut bran and straw have excellent water and fertilizer retention, and fly ash as well as gangue powder are rich in organic and mineral elements. The net-shaped biodegradable planting bag wrapped as the outer layer has certain heat insulation effect, and can regulate the soil environment in many aspects. The seeds inside the bags will sprout and grow after absorbing the nutrients inside the bags. The bags are flexible and can withstand a large degree of deformation without breaking and collapsing [28]. The bags are connected into a whole and effectively fixed with the slope, to realize the role of slope protection, soil as well as water conservation and greening. The mechanism, advantages, disadvantages and the scope of application of each soil improvement technology are shown in Table 1.

3.2.2. Vegetation cover technology. The selection of cover vegetation can be discussed in two directions: different vegetation types (herbs, shrubs, trees, etc.) and different species of each type.

For the selection of specific vegetation species, the following characteristics should be considered: good adaptability to adverse site factors and atmospheric factors; nitrogen fixation ability, well-developed root system, fast growth rate, high survival rate, abundant seed sources and easy seedling raising methods, etc. For vegetation cover methods, Zhang [18] and Niu [19] elaborated from different perspectives. Their division methods and corresponding vegetation cover methods are shown in Table 2.

| Classification Method | Reason | Vegetation Cover Method |
|-----------------------|--------|-------------------------|
| By gangue mountain reclamation stage | The mixed grass and irrigation forest maximizes the use of three-dimensional space, so that the artificial community shows a vertical distribution and horizontal mosaic similar to the natural community [27]. | The initial stage can be restored by grassland first; the later stage adopts the combination of grass, irrigation, forestry and multi-species. |
| By gangue yard different space location division | Different species have different needs for water and heat resources, different competitive strengths and weaknesses. In the meanwhile, appropriate configuration of herbs of Asteraceae and Cruciferae can improve the landscape; | In the ecological greening of the platform, the plant configuration adopts species of grass, legume, chrysanthemum and cruciferous; in the ecological greening of the slope, plants of grass and legume are used to green the slope, followed by vine plants at the bottom of the slope; on both sides of the approach road, street trees are used to green the road. |
4. Conclusion
The special physicochemical characteristics cause a certain degree of damage to the ecological environment of the mining area, which is a major obstacle on the road of green mining and ecological civilization construction in China. As an important means of green mine construction, ecological restoration is a necessary way to achieve green economic development in mining areas.

For two kinds of gangue mountain ecological restoration mode, treating while heaping with its effectiveness of restoration and treatment, timely restoration and treatment of damaged ecological environment, effectively alleviate the contradiction between coal resources development and utilization as well as environmental protection to maximize the overall benefits of both, which is the key research direction of gangue mountain ecological restoration mode. At present, the domestic and foreign "heap-by-healing" model has not been fully promoted, and should be adapted to local conditions, integrating various new technologies and materials, and strengthening the adjustment and optimization of the implementation plan.

For all kinds of ecological restoration technology of coal gangue mountain, mountain shaping is the foundation, which determines the stability of the gangue dump. Soil improvement is the key, which relates to the feasibility of reclamation and greening. Vegetation cover is the focus, which is the prerequisite of the ultimate effectiveness of ecological restoration. When carrying out the technology, one of the three is indispensable. The choice of restoration and management technology should be based on the characteristics of the accumulation of coal gangue mountain, the regional environment in which it is located, the area of the surrounding site, the distance of earth transportation and other comprehensive consideration of appropriate management measures.

In the future, we should strengthen the application and popularization of new green technology to avoid secondary pollution. We should ensure the high rate of reclamation while reducing the construction volume as much as possible to reduce the consumption of human and financial resources; as much as possible to achieve local materials, to waste to waste; strengthen the selection of reclamation species; at the same time to develop a complete monitoring and early warning mechanism of the ecological environment of the mine to achieve good restoration results, and to regard "green mine" as the ultimate goal.

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