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Recent Advance in the Application of Municipal Sludge Treatment

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ABSTRACT

The rapid expansion of wastewater treatment capacity has led to a corresponding sharp increase in sludge production. The safe disposal of municipal sludge has thus become a critical constraint on the further development of the wastewater treatment industry. This sludge is primarily generated by municipal wastewater treatment plants and consists of microbial biomass, organic debris, and inorganic particulates. Water within sludge exists in four forms: free water, interstitial water, surface water, and bound water. The dewatering process typically involves conditioning, thickening, and mechanical dewatering. During this process, extracellular polymeric substances (EPS) are the primary factor that impedes efficient dewatering. Currently, municipal sludge treatment faces three main challenges: high moisture content, high carbon emissions, and difficulty in resource recovery. Therefore, advancing research on sludge dewatering is essential for the overall progress of the wastewater treatment sector. This paper reviews recent research in the field of municipal sludge disposal. It begins by examining the physicochemical properties of sludge and then introduces the principles behind conventional treatment methods. The analysis explains the underlying reasons for the difficulty in reducing moisture content. The findings are intended to serve as a reference for technology selection and policy formulation in this field.

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Introduction

As urbanization accelerates, the volume of municipal sludge continues to rise, accompanied by increasing public demand for a higher-quality living environment. Improper disposal not only consumes valuable land through landfill use but also risks secondary environmental pollution due to the release of nutrients, heavy metals, and other pollutants contained in the sludge [1]. Traditional landfill-dependent disposal methods are no longer suitable in an era characterized by land scarcity and the need to reduce carbon emissions. To address the challenges posed by high moisture content namely the large footprint required for sludge management and the high energy consumption involved in treatment researchers have developed methods such as advanced dewatering, anaerobic digestion and pyrolysis carbonization [2]. These approaches aim to provide immediate solutions by focusing on reducing moisture content, minimizing sludge volume, and enabling resource recovery.

Composition of Municipal Sludge

The sludge generated from biological processes in wastewater treatment is known as biological (activated) sludge, which concentrates the pollutants present in the wastewater. The dewatering performance of this type of sludge is influenced by hydrophilic biopolymers (EPS) [3]. It contains not only a large amount of water present in interstitial, internal, adsorbed, and capillary bound forms but also various hazardous substances, including microorganisms, parasite eggs, recalcitrant organic compounds, and heavy metals [4]. The structure of the sludge flocs is shown in Figure 1.

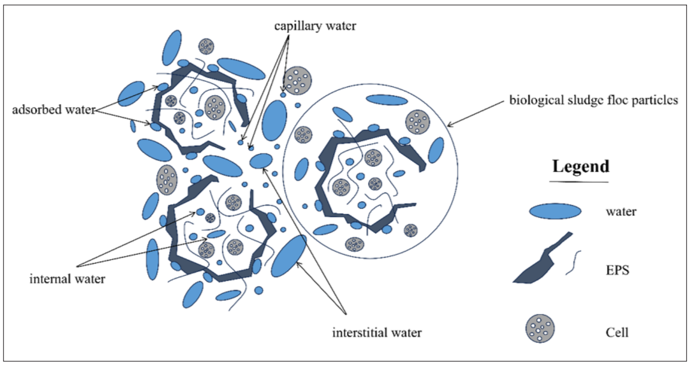

Figure 1: The Structure of the Sludge Flocs

Microorganisms in municipal sludge secrete large amounts of EPS, which bind together cells, colloidal particles, and inorganic matter [5]. The water-absorbing nature of EPS makes the sludge flocs resistant to rupture during mechanical dewatering, thereby hindering moisture removal. The water present in sludge is complex, consisting of free water, interstitial water, surface water, and bound water, with bound water being the primary obstacle to dewatering [6,7]. Sludge particles carry a negative surface charge, causing mutual repulsion that prevents natural settling [8]. In addition, sludge flocs are highly compressible, which readily leads to channel clogging, and their high organic content facilitates hydrogen bonding with water molecules, further enhancing water retention. Collectively, these factors account for the difficulty in dewatering municipal sludge.

Conventional Sludge Dewatering Process

Generally, free water can be removed by thickening, while interstitial water requires greater mechanical force to be separated. Adsorbed water is typically removed by combining coagulants with mechanical action to separate solids from liquid. Bound water which includes water associated with extracellular polymeric substances and water within cells requires disruption of the EPS structure or cell membranes to convert it into free water before removal [9,10]. Conventional sludge dewatering technologies include thickening, mechanical dewatering, and advanced dewatering. Thickening and mechanical dewatering are typically carried out at wastewater treatment plants, reducing the sludge moisture content to approximately 80% [8]. The sludge is then transported to dedicated treatment facilities for further advanced dewatering, where pretreatment is applied to improve dewaterability, followed by processes such as high-pressure filtration and thermal drying. The resulting dried sludge is then either properly disposed of or reused. The dewatering process is illustrated in Figure 2.

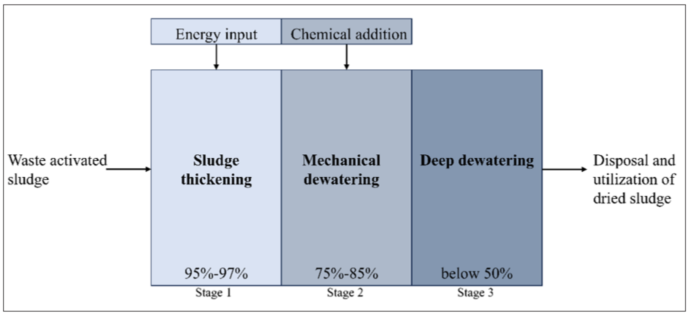

Figure 2: Flow Chart of Sludge Dewatering

Sludge Thickening

Sludge thickening primarily removes free water from the interstitial spaces, which is not bound to the sludge and is therefore easier to remove than bound water. The main thickening methods include gravity, dissolved air flotation, and centrifugal. Centrifugal has the highest energy consumption but offers high efficiency and a smaller footprint compared to gravity thickening. Gravity thickening is the simplest to operate, has low energy demand, and is more economical. Dissolved air flotation thickening falls between the two in terms of performance, but its relatively complex operation makes it less commonly used. Gravity thickening is the most widely adopted method, typically reducing the sludge moisture content to around 95%. This process requires relatively little energy.

Mechanical Dewatering

Mechanical dewatering primarily targets interstitial water. By adding flocculants, the structure of the sludge is altered, allowing moisture to be released more readily. Common techniques used to reduce the moisture content include plate-and-frame filter pressing, belt filter pressing, vacuum filtration, and centrifugal dewatering. However, the hydrophilic nature of extracellular polymeric substances (EPS) limits the efficiency of mechanical dewatering [11]. Therefore, pretreatment is necessary to reduce the moisture content, improve dewaterability, and minimize sludge volume. This in turn lowers subsequent transportation and disposal costs and simplifies overall handling. Sludge dewatering pretreatment methods are generally divided into physical and chemical approaches. Physical methods alter sludge properties through means such as heat treatment, freeze-thaw cycling, or microwave irradiation. Chemical methods involve the addition of acids, bases, surfactants, oxidants, or coagulants to modify the chemical characteristics of the sludge [12]. Among these, coagulation has attracted considerable attention due to its low cost and high efficiency.

Filter Press

A plate-and-frame filter press consists of an assembly of filter plates and frames with grooved surfaces arranged in a regular sequence. This equipment typically operates in a batch mode, resulting in relatively low throughput. However, it provides a high filtration driving force, yielding a dry filter cake that can be recovered for further use. Within the enclosed filtration chamber, pressure is applied to force the liquid in the suspension through the filter cloth, while solid particles are retained on the cloth [13]. The principle of this solid-liquid separation is illustrated in Figure 3.

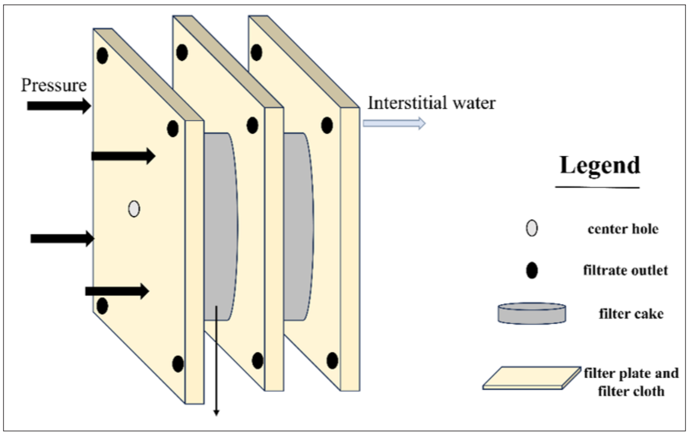

Figure 3: Principle of Plate and Frame Filter Press

Belt Filter Press

Thickened sludge is thoroughly mixed with a flocculant at a controlled concentration in a static or dynamic mixer, causing fine solid particles to aggregate into larger flocs while releasing free water. The flocculated sludge is then transferred to a gravity drainage belt, where free water is separated by gravity, resulting in a sludge mass that no longer flows freely [14]. Subsequently, the sludge is sandwiched between two moving filter belts and passes sequentially through a wedge-shaped pre-pressure zone, a low-pressure zone, and a high-pressure zone. Under progressively increasing compressive and shear forces, the sludge is gradually pressed to achieve maximum solid-liquid separation, ultimately forming a filter cake that is discharged. The principle is illustrated in Figure 4.

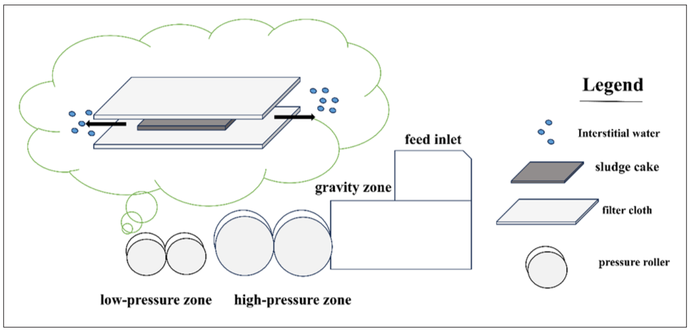

Figure 4: Schematic Diagram of Belt Filter Press

Vacuum Filtration

A common type of vacuum filtration equipment is the rotary drum vacuum filter, which consists of a hollow drum, a sludge tank, and a filter cloth. The interior of the drum is divided into multiple compartments. Under vacuum pressure, sludge immersed in the tank is drawn onto the filter cloth. As the drum rotates into the reverse blow zone, compressed air is applied to dislodge the accumulated sludge cake [11]. The advantages of this method include continuous operation, stable performance, full automation capability, high throughput, and suitability for dewatering various types of sludge. However, its disadvantages are that the sludge requires pretreatment prior to dewatering, the system involves a significant amount of auxiliary equipment, and the operating costs are relatively high.

Centrifugal Dewatering

The basic principle of sludge centrifugal dewatering is the separation of solids from liquid through the rotation of a centrifuge. Compared to a vacuum filter with equivalent throughput, a centrifuge requires a smaller footprint and has lower capital costs, although its energy consumption is higher. Common types of centrifugal dewatering equipment include rotary drum, disc, and plate centrifuges [15]. The rotary drum centrifuge is suitable for dewatering sludge generated from municipal wastewater treatment, achieving a cake moisture content of 70–90%. The disc centrifuge is suited for treating dilute or oily sludge, producing a cake with a moisture content of approximately 95% [12]. This method offers advantages such as simple operation, a compact design, high dewatering efficiency, and the ability to handle sludge that is difficult to dewater. However, it has drawbacks including relatively high solids content in the filtrate and substantial power consumption.

Flocculation Mechanism

The mechanisms of flocculation include Charge Neutralization, Adsorption Bridging, Sweep Flocculation /Enmeshment and Double Layer Compression.

Charge Neutralization, Sludge particles typically carry a negative surface charge, causing them to repel one another. Flocculants neutralize this negative charge, reducing electrostatic repulsion and allowing the particles to collide and eventually settle [16]. Adsorption Bridging, Long-chain polymeric flocculants adsorb onto multiple particles through their molecular chain length and adsorption sites, linking the particles together like bridges to form large flocs [17]. Sweep Flocculation /Enmeshment, When added at high dosages, inorganic flocculants form substantial metal hydroxide precipitates. During sedimentation, these precipitates act like a net, enveloping and sweeping up suspended particles, thereby carrying them into the settled solids [18]. Double Layer Compression, Adding electrolytes increases ionic strength, which compresses the electric double layer surrounding the particles. This reduces the zeta potential and weakens electrostatic repulsion between particles, thereby promoting coagulation of sludge particles [19]. In summary, flocculation in sludge dewatering typically involves the synergistic interaction of multiple mechanisms. In practice, the choice of flocculants and their combinations should be adapted to the sludge properties and the dewatering equipment used.

Deep Dewatering

In municipal sludge treatment, deep dewatering typically refers to the process of further reducing the moisture content of sludge from approximately 75–85% after mechanical dewatering to below 50% [20]. This step is essential for achieving sludge volume reduction and stabilization, and it also prepares the sludge for subsequent treatment or disposal. Common methods include electro-osmotic dewatering, thermal drying, and biological drying.

Electro-Osmotic Dewatering

Electro-osmotic dewatering combines mechanical pressure with a direct-current electric field. The electric field leverages the electro-osmotic flow between negatively charged sludge particles and water molecules, causing adsorbed water and some bound water to migrate toward the cathode, thereby achieving efficient solid liquid separation [21]. This method can reduce the moisture content to 50-60%, and it is particularly effective for sludge with high organic content. Its advantages include the absence of chemical additives and a high degree of volume reduction. A drawback is the complexity of the equipment, which limits its range of applications.

Thermal Drying

Thermal drying is the most effective method for volume reduction in advanced sludge treatment. It evaporates moisture by applying heat, enabling the water content of municipal sludge to be reduced to very low levels (10–40%) [22]. The main drawback is its high energy consumption. Future developments could leverage waste heat from power plants, waste incineration facilities, or industrial processes as drying heat sources, which would significantly reduce both energy use and treatment costs [23].

Biological Drying

Biological drying relies on heat generated by aerobic microbial respiration to evaporate moisture from sludge while also achieving partial stabilization. This process can reduce the moisture content to 50–65% [24]. Its advantages include the absence of external energy input, making it low in carbon emissions and energy consumption. However, drawbacks include a long processing time, a large spatial footprint, and applicability only to sludge with high organic content, which limits its range of uses.

Conclusions

The technical challenges of deep dewatering primarily stem from the physicochemical properties of sludge, particularly the binding of bound water by extracellular polymeric substances (EPS). Conventional methods such as conditioning and mechanical dewatering face limitations in overcoming this barrier, resulting in high sludge moisture content, elevated carbon emissions, and difficulties in resource recovery. This paper reviews the progress in understanding sludge characteristics and the mechanisms underlying existing dewatering technologies. It argues that future approaches to municipal sludge treatment should shift from optimizing single processes to integrating multiple processes in series, thereby achieving synergy among different technologies. Bio-drying holds considerable potential for future applications. Unlike conventional thermal drying, which relies on external heat sources, bio-drying offers significant advantages in terms of low energy consumption, low cost, and environmental friendliness. Its drawbacks include a long processing time and a large spatial footprint. In the future, it can be integrated with other treatment methods by using bio-drying as a pretreatment step before applying other drying technologies, thereby reducing the overall energy consumption of the treatment process.

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