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EKDIM – AN ELECTROKINETIC PROCESS TREATS MUNICIPAL WASTEWATER SLUDGE FOR SAFE LAND APPLICATION

EKDIM – ELEKTROKINETYCZNY PROCES WPŁYWAJĄCY NA OCZYSZCZANIE ŚCIEKÓW MIEJSKICH

Wastewater and water treatment plants generate enormous amounts of sludge every year. The treatment of the sludge typically involves a series of unit operations comprising of thickening, conditioning, dewatering, stabilization, disinfection and rarely, if ever, metal removal. This paper describes a new system of Electro-Kinetic Dewatering, Inactivation of pathogens and Metal removal (EKDIM) that facilitates simultaneous dewatering, metal removal and disinfection of sludge using one treatment unit. The process upgrades the sludge to above the Class A/ Exceptional Quality level as defined by US EPA. The system is based on electrokinetic (EK) phenomena initiated by of DC current to sludge. A series of tests were performed on anaerobically digested sludge, combined primary and secondary sludge, and primary sludge. The tests were successfully replicated in a pilot scale. Results showed that the system EKDIM is able to reach the dewatering level of 90% TS. The removal of metals such as Cr, Ni, Cd, Pb, Fe, Zn, Cu were above 70%; some final concentrations of metals were below the detection limit. In addition, the inactivation of Fecal Coliform, Salmonella sp, reovirus, Clostridium p. spores, and Ascaris suum ova was observed. Subsequently, it was demonstrated that biosolids generated during the EKDIM treatment processes can be transformed to a high quality soil amendment. This new technology can be safely applied to agricultural land farming. Although, the study was performed in batch EKDIM systems (disposal ponds, lagoons, reservoirs) the technique can be also applied to continuous flow conditions. The EKDIM system can target sludge generated by: i) municipal wastewater treatment plants, ii) water treatment plants, iii) pulp and paper industry, and iv) food processing industry.

1. Introduction

Sustainable management of biosolids should be the goal in wastewater treatment plants throughout the world. In Canada alone, the current production of biosolids is around 667,000 tones per year [1]. Biosolids recycling is therefore encouraged and regulated by American, Canadian, and European Environmental Agencies. Due to very strict regulations on biosolids land application, upgrading from Class B to Class A is becoming crucial [2,3]. Class A biosolids term denotes sewage sludge that has undergone treatment by processes that further reduce pathogen concentrations (so called *PFRP* processes) resulting in an end product that is safe for variety of agricultural uses. The Class A category is achieved when the following pathogens have reached limits:

- Enteric viruses (<1/4g TS),
- Salmonella (<3/4g TS).
- Viable helminth eggs (<1/4g TS) [4]

The US EPA 503 Regulations established the ceiling concentrations for nine metals that are usually found in municipal wastewater: arsenic, cadmium, copper, mercury, lead, molybdenum, nickel, selenium, zinc. Although Class B biosolids also must meet the heavy metal limits, the use of Class B solids (e.g. after mesophilic anaerobic digestion which is a process that significantly reduces pathogens or *PSRP* process) requires restricted public access and special precautions for exposed workers handling biosolids. To protect public health, the EPA 503 rule prescribes a restricted period of up to 1 year to limit public access to lands where Class B biosolids have been applied. This allows time for the natural die-off of most pathogens in the soil. As a rule, the most effective control for public health hazards is to eliminate them through substitution with Class A biosolids (i.e. after a process that can be categorized as *PFRP*) would eliminate the public health concerns. If the biosolids can meet exceptional quality (EQ) requirements of Class A, they may be sold in bags and applied in the same way as other soil conditioners such as compost or peat moss.

The EKDIM technology, which stands for Electro-Kinetics, Dewatering, Inactivation of pathogens and Metal removal, was developed and tested at both bench and pilot scale. It was demonstrated that application of direct current into specially designed electrode systems through the biosolids slurry initiated electrokinetic phenomena, which can be controlled within the EKDIM technology and which lead to the upgrade of biosolids to Exceptional Quality/Class A level and above. Although electrokinetic methods for sludge dewatering exist on the market [5] the electrokinetic simultaneous dewatering, disinfection and metal removal has not been implemented before.

Esmaeily et al. effectively demonstrated the heavy metal removal and the inactivation of fecal coliform in combined primary and secondary biosolids using an electrokinetic dewatering system [6]. Through the application of DC voltage potential to biosolids between a series of anode and cathode electrodes a number of electrokinetic phenomena occur e.g. electro-osmosis, electrophoresis, electro-flocculation and electrolysis. The effect of a direct current applied to electrodes immersed in a porous media, generates movement of charged species to respective electrodes as well as the movement of interstitial water freed from bio-flocs and its drainage out of the sludge. During this process, diverse electrochemical reactions occur at the electrodes; primarily, the electrolysis of water producing H_2 (g) and OH^- (aq) at the cathode and O_2 (g) and H^+(aq) at the anode. These charged species, OH^- and H^+ migrate creating basic and an acid fronts (an oxidation and reducing zones) respectively [7].

This paper outlines the results of a series of bench scale and pilot scale EKDIM tests conducted under varying conditions; notably, high and low voltage gradients, and the addition of different conditioners. To broaden the application of EKDIM technology sludge of different origin was used in this research: primary sludge (PS) alone, PS combined with attached growth biosolids, combined PS with waste activated sludge (WAS), and anaerobically digested (combined PS and WAS) biosolids. Sludge was collected from wastewater treatment plants in Auteuil QC, Ottawa ON, and Syracuse NY.

2. Bench-Scale Studies on Electrokinetic Dewatering and Pathogen Inactivation

The working volume for these tests was 650 mL of biosolids, containing between 2.4 and 4.3% TS depending on the sludge origin. The samples were poured into the dedicated EK reactor-cells 1 to 10 (Table 1). Reactors 11, 12, 13, and 14, were filled exclusively with anaerobically digested sludge (Ao) and inoculated with reovirus (Table 2.). An amphoteric conditioner (1.3% w/v) was added to EK reactors number 1,3,5,7,9,11,12,13, and 14. Biosolids in reactors 11, 12, and 14 were also exposed to commercial disinfection enhancers: Glutaraldehyde and Bioxy S, to verify the impact of EK on the biocide's behavior (Table 2). During these operations, the gravitationally drained liquid from anode and cathode was collected to gauge the EK activity. The EK reactors 1 to 10 were inoculated with *Salmonella spp* at the level of 10^9 to 10^{11} cfu/mL, while the EK reactors 11 to 14 were inoculated with reovirus at the level of 1.1×10^7 pfu/mL. In addition, *Clostridium perfringens* bacteria were inoculated in EK reactors 5 to 10. Endogenous fecal coliform (FC) was analyzed in all reactors. A DC power supply was connected to the reactors and the desired voltage gradient was set at low, medium or a high range (all less than 5V/cm). The tests were conducted over a 1 to 9 days period. Four reactors (1 - 4) without covers were exposed to double action of EK and forced air convection (blower) to simulate real environmental conditions in exposed lagoons. The control cells without supplying electrical potential were also prepared for all reactor conditions.

Tab. 1. Lab experimental conditions and pathogens monitored: FC, Salmonella spp., Clostridium perfringens

Reactor No.	Sludge samples	System Applied	Voltage gradient	Amphoteric conditioner
1	Comb.Attach. Gr.	EK + Blower	Low	Yes
2	Comb.Attach. Gr.	EK + Blower	Low	No
3	Anaerobic	EK + Blower	Low	Yes
4	Anaerobic	EK + Blower	Low	No
5	Primary, Ct	EK	High	Yes
6	Primary, Ct	EK	High	No
7	Comb. WAS, Ct	EK	High	Yes
8	Comb. WAS, Ct	EK	High	No
9	Anaerobic, Ct	EK	High	Yes
10	Anaerobic, Ct	EK	High	No

Legend: *Comb = Combined primary and secondary sludge; Attach. Gr. = Attached growth secondary sludge; WAS = Waste activated sludge; Anaerobic = Anaerobically digested sludge, Ct = Clostridium perfringens inoculation; EK = application of DC*

Tab. 2. Experimental conditions for reovirus and Clostridium p. spores in reactors with anaerobically digested sludge

Reactor No.	Voltage gradient	Exposure time (days)	Glutaraldehyde (% v/v)	Amphoteric Conditioner (% w/v)	Bioxy S/ (T.A.E.D) (% w/v)
11	High	3	0.5	1.3	0.2
12	Medium	1	0	1.3	0.4
13	Low	1	0	1.3	0
14	Low	3	0.2	1.3	0.1

2.1. Dewatering

The results demonstrated (Fig.1) that all types of sludge responded successfully to EK dewatering, particularly when an "amphoteric" conditioner was applied. The combined (PS + WAS) sludge reached 75% total solids TS (max 99%) at bench scale. The initial total solids ranged between 2 and 5%. The dewatering of primary sludge led to an average 75% TS (max 85%), Although the treatment of anaerobic digested sludge has achieved lower average TS (between 20% and 55%) than that of the primary and mixed sludge – the results were still much better than those from conventional dewatering equipment. The highest TS content was produced in reactors with the lower voltage gradient which initiated slower electro-coagulation process, and then formation of flocs with more compacted structure and higher solids content; thus the higher removal of water was obtained. The dependent parameters are electrical field strength, sludge physical properties (e.g. floc formation related to diffuse double layer), type of sludge, total volatile solids (TVS), pH, and conductivity. Some of these parameters are affected by the use of conditioning liquids. Among all type of water associated with a floc (hydration, vicinal, interstitial, and free water) only EK treatment was able to simultaneously affect all of the fractions of water bound to the sludge particles leading to more efficient dewatering than in the conventional dewatering (e.g. high-shear centrifuges or various thermal methods).

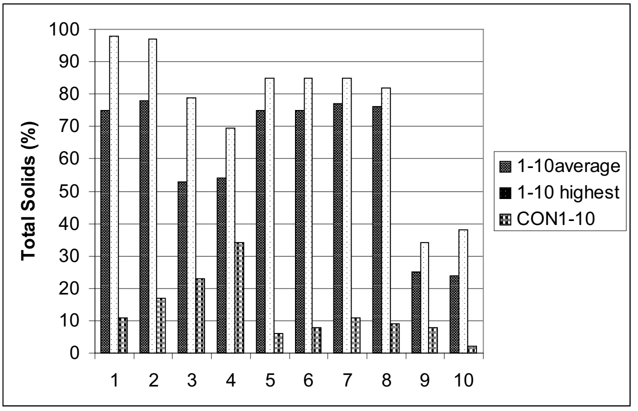

Fig. 1. The average and the highest TS content in ten EK lab reactors and ten control cells (CON)

2.2. Metal removal

All results demonstrated mobilization of metals due to the EK phenomena. The EK metal removal, transport of the metals with the catholyte (liquid collected on the cathode) or captured on electrodes, was observed in all the types of biosolids tested. EK phenomena enhanced with "amphoteric" conditioner created satisfactory conditions for metal removal. A complete removal of lead was achieved in lab scale with the higher concentration of conditioner. Some 73% lead removal was confirmed in pilot scale, with the lower concentration of conditioner. In all cases the resulting metal concentrations in sludge after dewatering were below allowable levels for class A biosolids. The differences observed in various metal removals were associated with a different speciation of metals under different EK conditions. In general, lower current applied over a longer period led to superior overall results for heavy metals removal.

In order to assess the best conditions for metal removal from sludge under EK phenomena, a series of simulation studies were also performed using the software Visual MINTEQ adapted to the biosolids conditions. These studies showed that the EKDIM changed the forms of metals. The principal transformation was from organometallic complexes to mobile ionic forms. These forms accelerate ionic and electro-osmotic transport of metals, mostly towards the cathode. A new databank was created for the purpose of biosolids management and a number of relationships were generated for large pilot scale and full-scale applications of the EKDIM technology.

2.3. Pathogen inactivation

The following indicators of inactivation were considered: fecal coliform (FC) – an indigenous bacteria, *Salmonella spp*. – an indigenous and introduced bacterial indicator, reovirus – an introduced viral indicator substitute for polio virus, *Ascaris suum* ova – an introduced helminth, *Clostridium perfringens* – an indigenous bacteria and spores. Practically, no FC and *Clostridium perfringens* bacteria were detected in all EK cells and effluents (catholyte or anolyte) after application of EKDIM. A complete inactivation of *Salmonella* was observed in a significant number of tests – in fact all tested sludges met Class A criteria. A number of technological specifications were described. For example, anaerobically digested sludge reached better inactivation of *Salmonella spp* and dewatering under lower voltage conditions. However, combined sludge achieved better inactivation under higher voltage while the dewatering efficiency was better under lower voltage conditions. Studies on inactivation of *Clostridium perfringens* spores, reovirus and *Ascaris suum* ova included testing of a combination of three conditioners; two of them were provided by the company Atomes. After 3 days of EKDIM treatment of anaerobically digested sludge, the 4.5·log reduction of *Clostridium perfringens* spores was observed. The most effective conditions were when GTA and Bioxy S/ TAED enhanced by electrokinetic phenomena (at the constant voltage of 0.7 V/cm) were applied. The work showed that EK system, GTA and Bioxy S/ TAED, as enhancer agents, are not sufficiently effective when used alone. In other words, spore inactivation could be obtained only through the combination of EK system and disinfection-enhancing agents. Assessment of the results showed that different factors, which attack numerous spore constituents, are involved in inactivation of *C. perfringes* spores in the EKDIM technology; these including the spore coating, proteins, unsaturated lipids, respiratory enzymes, and peptidoglycans. Reactions produced during the EK phenomena help to create effective oxidative zones, which neutralize protective systems inside and outside of *C. perfringens* spores.

It was also observed that EKDIM technology was successful in virus inactivation. All applied conditions were successful in achieving the desired 10-log reduction of reovirus in anaerobically digested biosolids. Furthermore, application of enhancement agents, GTA, Bioxy S/ TAED, improves inactivation effect. The established reactivity of GTA with proteins suggests that the viral capsid or viral-specific enzymes are vulnerable to GTA treatment. It is surmised that the “amphoteric” conditioning agent is important in the simultaneous dewatering process. The developed combination of electro-biochemical processes plays a significant role in inactivation of reovirus in EKDIM system.

Similar processes are effective in inactivation of helminths. A complete inactivation of *Ascaries suum* ova after application of EKDIM was found in both combined and anaerobically digested sludge. Alteration of the egg’s inner lipid membrane integrity at the higher electrical field strengths could have been found at the higher ionic concentrations of the “amphoteric“ conditioner. This increased permeability can render the eggs more susceptible to its disinfection effects. If critical electrical field strength is exceeded, the membrane is subjected to pore formation. One can speculate that the higher concentrations of added conditioner in the extracellular medium above a critical level resulted in irreversible damage to the egg’s inner membrane. It was assumed that a combined effect of electrochemical by-products and ammonia presence created by EKDIM was at the source of *Ascaris* eggs inactivation. The cells without the conditioners exhibited no inactivation any of the applied voltage gradients.

3. EKDIM Pilot Scale Studies

The results from bench tests were analyzed and optimal conditions for EKDIM were tested in pilot scale unit. In these tests, a pilot scale unit containing approximately 50 liters of sludge was utilized in each of the four tests: three on combine (primary and WAS) sludge and one on anaerobically digested biosolids from the same wastewater treatment plants listed above. Table 3 present the characteristics of the untreated biosolids utilized. The tests were performed to study the impact of EK on the dewatering and heavy metals removal of the sludge. The pilot unit was subjected to direct current applied through arrays of perforated cathodes and anodes. The liquid discharge method varied between the cathode and anode; the catholyte drained by gravity from the cathode while the anolyte was discharged via pumps. Care was taken to avoid creating a hydraulic force generated by the pump; the pump was set to run periodically and thus it discharged only the liquid accumulated inside the electrodes.

Various test conditions were altered to detect if any the effect of some parameters on the removal efficiency. These test conditions are outlined in table 4. In order to determine the heavy metal removal efficiency analysis was performed on nickel, lead, iron, zinc, copper and cadmium. The tests were run under forced air convection to simulate real environmental conditions in exposed lagoons. The energy consumption and several additional parameters (ammonia, nitrate, nitrite, phosphate, sulfate, and chloride) were investigated during the experiments.

Tab. 3. The initial composition of sludge used in the pilot scale tests

Sludge Type	Solid Content %	Anions (mg/kg TS)					
		Ammonia	**Nitrate**	**Nitrite**	**Phosphate**	**Sulfate**	**Chloride**
Comb. WAS Test #1	5.39	1899	35	ND	14114	2374	3917
Comb. WAS Test #2	3.50	680	22	ND	-	ND	2517
Anaerobic Test #3	2.28	24518	280	ND	2749	ND	9257
Comb. WAS Test #4	2.28	25584	336	ND	2721	ND	9257
	pH / Redox	**Metals (mg/kg TS)**					
		Lead	**Iron**	**Copper**	**Cadmium**	**Nickel**	**Zinc**
Comb. WAS Test #1	6.92/ -0.5	24	37214	341	0.74	186	478
Comb. WAS Test #2	6.94 / -0.9	89	8490	105	0.29	342	151
Anaerobic Test #3	9.01/ -16.5	45	159274	268	0.50	448	1012
Comb. WAS Test #4	7.02 / -6.7	85	8278	450	0.75	1050	895

ND: not detectable

Tab. 4. Pilot test conditions

Test No.	Sludge type	Conditioner concentration (g/l sludge)	Electrodes distance (cm)	Voltage gradient	Pumps to discharge from anode	Test duration (days)
1	Comb. WAS	13	50	low	0	5
2	Comb. WAS	26	50	low	1	15
3	Anaerobically digested	13	74	high	2	5
4	Comb. WAS	13	74	high	2	5

3.1. Dewatering

The control of the pilot unit was very critical in reaching high dewatering (discharge rate) while keeping the system's temperature under optimal conditions. Results from these pilot tests demonstrated good dewatering capacity up to 70% TS. The dewatering rate in tests no.3 and no.4 was higher than in the first two tests. In the tests no.2, 3 and 4 in which drainage was applied from both anode and cathode better results are observed and the anode section exhibited greater dewatering rates than in the cathode part. Overall, the best result, about 70% TS, was observed in test no.3 under the higher voltage gradient and the application of both gravity discharge from the cathodes and the pumped drainage from the anodes.

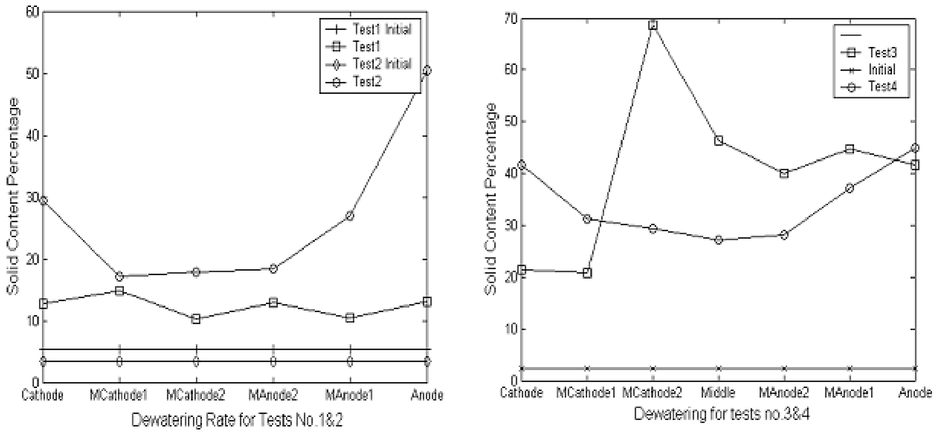

Fig. 2. Total solid content of dewatered biosolids after pilot scale treatment

3.2. Metal removal

Heavy metal removal in this pilot test showed significant results for nickel, lead, zinc, and iron. The removal efficiency values are given in table 5 (where A,B,C,D present dehydrated sludge strips between 4 cathodes and 4 anodes). The iron removal varies from 20.3 to 82.5%. In the test no. 4 the removal of iron is not very effective due of high corrosion in the anode electrodes during this particular test. The presence of acidic environment in the test enhanced the mobility of species but also increase the corrosion of electrodes. However, based on the reactive anodes principle that defines electro-coagulation, the generation of metallic cations (Fe^{3+}) in the sludge act as a coagulant and lead to the destabilization of suspended particles and colloidal structure. This excess iron in the system thus contributes to the dewatering capacity by enhancing the flocculation of suspended matter in the sludge. Accordingly, the neutralization of ions and particle charges is more likely to reduce the water content to lower levels than is possible with chemical precipitation. This allows us to replace and/or reduce the use of expensive chemical agents (polymers and metallic salts).

Tab. 5. Efficiency of metal removal at the end of each test

Test Number	Row	Metals Mean Removal Efficiency (%)					
		Iron	Lead	Copper	Zinc	Cadmium	Nickel
1	A	62	57.1	69.1	45.3	60.9	72
	B	59.1	55.4	69.7	53.2	57.6	70
2	A	58.1	57.1	69	51.1	60.9	69.7
	B	56.3	54.1	68.8	45	55.7	67.6
3	A	82.5	34.2	47	54.4	54	51.1
	B	75.3	33	52.4	53.4	46.4	49.9
	C	78.1	24.9	46.2	54.4	53.1	51.4
	D	68.5	19	47.8	45.2	29.7	40.6
4	A	-	73.3	60.32	70.7	52.4	67
	B	-	72.2	46.7	71.5	51.4	58.7
	C	20.3	72.9	47.8	71.1	51.4	54.5
	D	30.1	72.3	51.6	69.6	56.2	60

Test no.4 showed the best results on average for heavy metals removal, especially lead and zinc, it also has good results for copper, cadmium and nickel removal. Test No.3 showed good results for heavy metals removal of anaerobic sludge. In general, uniform metal removal was observed throughout the thickness and length and it reached and even surpassed the allowable levels defined in rule 503 of the EPA regulations for biosolids applied to agricultural land, forest, public contact sites or reclamation sites. This experiment also demonstrated the higher impact of the voltage gradient on the removal efficiency over the conditioner effect. Overall, better removal was observed from combined aerobic sludge than from the anaerobically digested sludge. The result may be due to poor sludge digestion, which has a tendency to generate higher proportion of fine solids and colloidal material than are present in the raw sludge. The highest efficiency of EKDIM system was achieved when multifunctional electrodes were applied. Simultaneous removal of phosphorous (95%) and ammonia (68% to 98%) was observed. In some tests, an increase of temperature up to approximately 70^{o}C was generated that led to the pasteurization of biosolids, and in effect, to the disinfection of pathogens. It was shown that a careful control of amperage could significantly cut the costs.

4. Conclusion

EKDIM upgraded both mixed aerobic and anaerobically digested sludge to Class A /Exceptional Quality biosolids.The results show that the EKDIM configuration tested is able to reach the dewatering level of 90% TS at lower voltage gradient with the addition of the amphoteric conditioner and forced air convection.

The removal of metals, such as Cr, Ni, Cd, Pb, Fe, Zn, Cu, were above 70%; some of the final concentrations of metals were below the detection limit. These results clearly demonstrate the success of EKDIM process in the separating heavy metals from biosolids.

In addition, the inactivation of several pathogens and pathogen indicators: Fecal Coliform, *Salmonella spp,* reovirus, *Clostridium p.* spores, and *Ascaris suum* ova, was observed. This shows that the biosolids generated during EKDIM treatment processes can be transformed to a high quality soil amendment and safely be applied to land farming.

The cost of EKDIM varies with respect to the applied voltage gradient, the type of sludge, the configuration of electrodes, the current density, duration of exposure to EK, and the types and concentrations of applied conditioners. Based on the laboratory conditions, the operation cost (assuming \$0.03/kWh and conditioners) ranging between \$1.6 to \$28 per m^3 of liquid sludge, corresponds to an overall cost of \$50 - \$700 per tone of dried TS. For example, a dewatering of combined sludge (primary and secondary) to the level of 45% TS, including inactivation of FC, *Salmonella*, viruses, and *Clostridium*, as well as metal removal below allowable levels, may cost \$230 per tone of dry TS.

The main advantage of EKDIM is the reduction in overall sludge volume contributing to a significant disposal cost reduction in terms of transportation and landfill disposal by facilitating agricultural usage as exceptional quality soil amendment. The high dryness of the resulting biosolids facilitates storage and allows its transportation using standard vehicles. The reduction of heavy metal content and pathogens to a Class A level improves the quality of biosolids and allows their application too land application. Finally, there is a potential for operational cost reduction by minimizing the use of polymers to promote dewatering. The EKDIM technology is much more energy efficient when compared to thermal treatments of sludge giving comparable results in terms of TS content and disinfection.

This new technology can be safely applied to solids destined to agricultural land. Although the study was performed in batch EKDIM systems (disposal ponds, lagoons, reservoirs) the technique can be also applied to continuous flow conditions. The EKDIM system can be applied to sludge generated by: i) municipal wastewater treatment plants for raw primary, secondary sludge as well as anaerobically digested sludge, ii) water treatment plants, iii) pulp and paper industry, and iv) food processing industry.

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