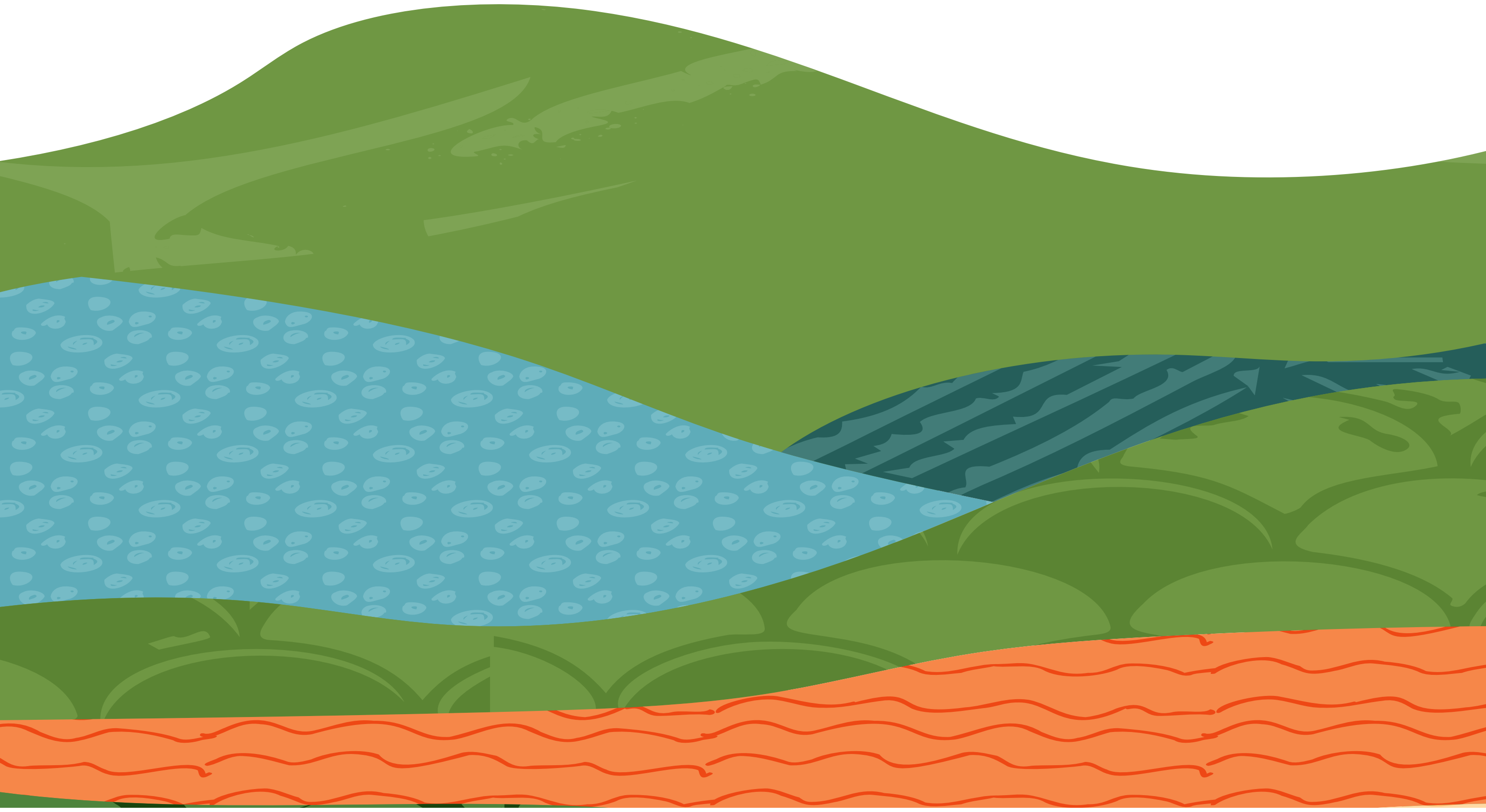
The Joint Water-Agriculture Ministerial Council

Safe Use of Sludge in Agriculture in The Arab Region

Draft for discussion



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Disclaimer

The report on the “Safe Use of Sludge in Agriculture in The Arab Region” was prepared and revised by the Regional Office for the Near East and North Africa of the Food and Agriculture Organization (FAO) to support the Joint Technical Secretariat of the Joint Ministerial Council (composed of the Technical Secretariat of the Arab Water Ministerial Council and the Arab Organization for Agricultural Development) in implementing the recommendation of the High-Level Joint Water-Agriculture Technical Committee emanating from its meeting held on 18 October 2022 on the Use of Non-Conventional Water Resources in Agriculture.

Abbreviations

SRT	Sludge Retention Time.
F/M	Food mass ratio.
OFMSW	Organic fraction of municipal solid wastes.
U.S. EPA	United States Environmental Protection Agency.
WWTP	wastewater treatment plant.
TSS	Total suspended solids.
VSS	Volatile Suspended Solids.
Y_{actual}	Actual sludge yield.
COD	Chemical Oxygen Demand.
WAS	Waste activated sludge.
BOD	Biochemical Oxygen Demand.
DS	Dry solids.
MFT	Modified filtration test
EQ	Exceptional quality
EC	European Comission
GHG	Green House Gas
$kgCO_2$-eq	Equivalent to carbon dioxide

1. General framework and main objectives

1.1 Background

The second Joint Water-Agriculture Ministerial meeting was held in January 2022 where Ministers of Water Resources and Ministers of Agriculture decided a set of resolutions on different topics, inter alia, the use of non-conventional water resources for agriculture.

The High-Level Joint Water-Agriculture Technical Committee (HLJTC), in its meeting held in October 2022, requested the Joint Technical Secretariat and FAO to prepare a paper on the safe use of sludge resulting from treated wastewater for agriculture in the Near East and North Africa region.

1.2 Scope

The objective of the paper is to provide decision makers at country level necessary background, information, data, and analysis to decide on future orientations and regional strategies on the safe use of sludge in agriculture in the Arab region.

The paper provides conclusions and possible strategic orientations related to the safe use of sludge for agriculture to support decision-making process.

2. INTRODUCTION

A main byproduct of wastewater treatment plants (WWTP) is sludge that is slurry with high content of suspended solids. The sludge is produced from (1) the raw solids exist in the raw wastewater that enters the WWTP which is called primary sludge, and (2) from the excess biomass which is one of the end products of the biological degradation processes which called secondary sludge. Approximately, 1-2 liter per person of concentrated sludge is typically produced from the municipal WWTP that receives around 100 to 200 L of sewage per person. The management of this by product solid waste quite complex and costly in terms of treatment, transportation, and final disposal due to its content of mainly heavy metals, pathogens, and water content, so as to be transported and also to comply with the enforced environmental legislations. The wasted sludge discharge is the largest in volume of the waste by products removed from the municipal WWTP. The big volume of the sludge is due to its high-water content, reaching 95%. Indeed, due to the continuous growth of population and industrial activities, the amount of sludge is dramatically increasing as one of the end products of wastewater treatment processes at the same pace.

The main challenging issues with sludge management are:

- Sludge volume is high due to its high-water content, and as such, the disposal is costly and complicated.
- Improper sludge disposal might cause in environmental pollution, including water sources, soil, plants and air with heavy metals, organic matter, pathogens, micro-pollutants, offensive odor, emission of NH_3, H_2S etc.

Since it recycles nutrients and organic matter into the soil, spreading treated sewage sludge on the field appears to benefit the agricultural sector among the management alternatives. Treated sewage sludge is also called bio-solids. However, in order to ensure sustainable recycling, environmental protection, as well as the health of people and animals, a carefully developed monitoring system of the region that receives the sludge should be implemented. In accordance with Article 4 of the Waste Framework Directive 75/442/EEC of the European Union, spreading waste over land is preferred when agricultural benefit is obtained, which is when doing so results in better soil conditions for crop growth while also preserving environmental quality (Doula *et al*., 2017). Treated sludge generally contains stabilized organic matter and nutrients (i.e., N, P, K, Ca, and Mg); thus, it has agricultural values. Nutrients contained in sludge can be safely used as fertilizer to stimulate plant growth and thus can increase crop harvest (EC, 2001; Pasda *et al*., 2005; U.S. EPA, 2023).

However, it is necessary to note that the legal framework that defines the framework of land spreading, such as the Waste Framework Directive 75/442/EEC as amended 91/156/EEC, Directives 86/278/EEC on land spreading of sewage sludge and 91/676/EEC on protection of waters against pollution caused by nitrates from agricultural sources, U.S. EPA/625/R-95/001, underestimates the role of soil or at least does not consider it as an internal (Doula *et al*., 2017). According to Directive 86/278/EEC of the European Union, farms ought to follow certain guidelines when using sewage sludge as fertilizer to avoid endangering the soil, plants, animals, and people while maintaining the quality of the soil, surface water, and groundwater. It sets specific limits on the concentrations of seven heavy metals allowed in soil that may be toxic to plants and humans.

Modern societies should implement policies to encourage the reuse of any resource that can be used, in accordance with the general and specific goals of sustainability. Land spreading of wastes is preferred to thermal destruction or landfilling in the ranking of choices, provided that a benefit to agriculture (or ecological improvement) can be proved (Waste Framework Directive issued by the EU, 86/278, EC). Sewage sludge should be viewed in this perspective as a secondary product to be utilized rather than as waste.

The current study is concerned with the requirements and prerequisites that should be met in order to guarantee the sustainable and secure reuse of sewage sludge on agricultural soils in the Arab countries. It is crucial to create and put into practice methods, processes, and instruments to monitor reuse areas before, during, and after application in order to maintain environmental sustainability.

3. Sludge managment

3.1. Sludge type and quality

Water makes up the majority of sludge; the dry solids concentration normally falls between 1 and 5 percent. The physical characteristics of various types of sludge are given in Tables 1 and 2. The biological treatment technology (trickling filter, activated sludge, RBC), the incoming wastewater (domestic or industrial), the type of sewerage system (combined or separate), and the operational regime (applicable loading rates, sludge age, etc.) all affect the composition of the sludge. The selection of sludge processing methods is influenced by the treatment plant's operating regime.

Table 1. Physical characteristics of various types of sludge

Sludge	Color	Other physical properties	odor	Digestibility (Amenability to further biological stabilization)
Primary sedimentation	Grey	Slimy	Extremely offensive	Readily digested
Chemical precipitation (primary)	Black, red surface if high in iron	Slimy, gelatinous, gives off considerable gas	Offensive	Slower rate than primary sedimentation
Activated sludge	Brown, dark if nearly septic	Flocculent	Inoffensive, earthy when fresh, putrefies rapidly	Readily digested
Trickling filter humus	Brownish	Flocculent	Relatively inoffensive, decomposes slowly	Readily digested
Digested sludge	Dark brown to black	Contains a very large quantity of gas	Inoffensive if thoroughly digested; like tar or loamy soil	Well digested
Septic tank sludge	Black		Offensive (H_2S) unless very long storage time	Mostly stabilized

Source: Loehr and Jewell (1979) cited in Polprasert and Koottatep (2017)

Table 2. Typical data for the physical characteristics and quantities of sludge produced from various wastewater treatment operations and processes

Treatment operation or process	Specific gravity of solids	Specific gravity of sludge	Dry solids, kg/10^3 m^3	
			Range	Typical
Primary sedimentation	1.4	1.02	110-170	150
Activated sludge (waste biosolids)	1.25	1.005	70-100	80
Trickling filter (waste biosolids)	1.45	1.025	60-100	70
Extended aeration (waste biosolids)	1.30	1.015	80-120	100a
Aerated lagoon (waste biosolids)	1.30	1.01	80-120	100a
Filtration	1.20	1.005	12-24	20
Algae removal	1.20	1.005	12-24	20
Chemical addition to primary tanks for phosphorous removal				
- Low lime (350-500 mg/L)	1.9	1.04	240-400	300b
- High lime (800-1600 mg/L)	2.2	1.05	600-1300	800b
Suspended growth nitrification	-	-	-	-c
Suspended growth denitrification	1.20	1.005	12-30	18
Roughing filters	1.28	1.02	-	-d

a Assuming no primary treatment.

b solids in addition to that normally removed by primary sedimentation.

c Negligible.

d Included in biosolids production from secondary treatment processes.

Adopted from: Metcalf and Eddy (2003).

Typical chemical compositions of raw and digested sludge are presented in Tables 3 and 4. High quantities of heavy metals, which are primarily associated to suspended solids, are particularly found in primary sludge. Sludge is frequently rendered inappropriate for agricultural reuse by heavy metals originating from industrial discharges, rainwater runoff, or traffic emissions and domestic sources like discharging septage that is usually rich in heavy metals. The potential for sludge reuse in area served with separate sewer systems is greater than that served with combined sewer systems.

Secondary sludge is mainly composed of biomass, which is produced during biological conversion of organic matter. Typically, the Y_{actual} of heterotrophic biomass 0.5-0.6 kgVSS/kg $COD_{biodegraded}$. The secondary sludge organic matter content is typically between 60-85%. The presence or absence of primary sedimentation affects secondary biomass production rates. Suspended solids in the (presettled) sewage may adsorb to the biomass flocs thereby adding to the secondary sludge production rates (Veenstra, 2002).

Biomass is a major component of secondary sludge and is produced as a product of the biological conversion of organic matter. Heterotrophic biomass typically degrades at a rate of 0.5–0.6 kgVSS/kg $\text{COD}_{\text{biodegraded}}$. The organic matter concentration of secondary sludge ranges normally from 60 to 85%. The rates at which secondary biomass is produced are impacted by the presence or non-presence of primary sedimentation tank. The production rates of secondary sludge are usually higher than the values calculated based on the sludge yield as a result of suspended solids in the sewage adhering to the biomass flocs. Potential contamination of secondary sludge is necessary to be carefully considered when primary settling tank is not included in the process.

Table 3. Typical composition of primary and secondary sludge generated at wastewater treatment plants (Metcalf and Eddy, 2003) [a]

	Untreated primary sludge		Digested primary sludge		Untreated activated sludge
Item	**Range**	**Typical**	**Range**	**Typical**	**Range**
Total dry solids (TS), %	5-9	6	2-5	4	0.8-1.2
Volatile solids (% of TS)	60-80	65	30-60	40	59-88
Grease and fats (% of TS):					
Ether soluble	6-30	-	5-20	18	-
Ether extract	7-35	-	-	-	5-12
Protein (%TS)	20-30	25	15-20	18	32-41
Nitrogen (N, % of TS)	1.5-4	2.5	1.6-3.0	3.0	2.4-5.0
Phosphorous (P_2O_5, % of TS)	0.8-2.8	1.6	1.5-4.0	2.5	2.8-11
Potash (K_2O, % of TS)	0-1	0.4	0-3.0	1.0	0.5-0.7
Cellulose (% of TS)	8-15	10	8-15	10	-
Iron (not as sulfide) (% of TS)	2.0-4.0	2.5	3.0-8.0	4.0	-
Silica (SiO_2, % of TS)	15-20	-	10-20	-	-
pH	5.0-8.0	6.0	6.5-7.5	7.0	6.5-8.0
Alkalinity (mg/L as $CaCO_3$)	500-1500	600	2500-3500	3000	580-1100
Organic acids (mg/L as HAc)	200-2000	500	100-600	200	1100-1700
Energy content, kJ/kg TS	23,000-29,000	25,000	9000-14,000	12,000	19,000-23,000

[a] Adapted in part from U.S. EPA (1979)

Note: kJ/kg x 0.4303 = Btu/lb

Table 4. Chemical composition of raw and digested sludge

Item	Raw Primary Sludge[a]		Digested Sludge[b]	
	Range	**Typical**	**Range**	**Typical**
Total dry solids (TS), %	2.0-7.0	4.0	6.0-12.0	10.0
Volatile solids (% of TS)	60-80	65	30-60	40.0
Grease and fats (ether-soluble, % of TS)	6.0-30.0	-	5.0-20.0	-
Protein (% of TS)	20-30	25	15-20	18
Nitrogen (% of TS)	1.5-4.0	2.5	1.6-6.0	3.0
Phosphorous (P_2O_5, % of TS)	0.8-2.8	1.6	1.5-4.0	2.5
Potash (K2O, % of TS)	0-1.0	0.4	0.0-3.0	1.0
Cellulose (% of TS)	8.0-15	10.0	8.0-15.0	10.0
Silica (SiO2, % of TS)	15-20	-	10.0-20.0	-
pH	5.0-8.0	6.0	6.5-7.5	7.0
Alkalinity (mg/L as $CaCO_3$)	500-1,500	600	2,500-3,500	3000

[a] Refer to sludge settled in primary sedimentation tanks.

[b] Mostly refers to anaerobically digested sludge.

Source: Loehr *et al.* (1979) cited in Polprasert and Koottatep (2017)

3.2. Sludge quantity

3.2.1.Primary sludge Production rates

According to the USA Environmental Protection Agency, daily production rates of suspended solids range from 70 to 110 g TSS/capita.day. The primary sludge generation rate is 50–75 g TSS/capita. day assuming a typical settling efficiency of 65%. When compared to field data from Europe, this is quite high. These high primary sludge production rates in the USA could be attributed to the widespread usage of kitchen grinders there. The amount of primary sludge produced by municipal sewage in Europe varies according to the type of sewage system used. In separate sewer systems, the total suspended solids (TSS) produced varies from 40 to 50 g/ capita.day; in combined sewer systems, it can reach up to 60 g/cap/day. It brings the primary sludge production rate to 30 gTSS/ capita.day in separate and 40 g TSS/capita. day in combined sewer systems, assuming a normal 70% of TSS to settle in primary settling tanks (Polprasert and Koottatep, 2017).

Data on sludge production in developing countries are not readily available because most cities do not have adequate sewerage systems for wastewater transportation to central treatment plants. However, it can be estimated that each person generates 25–40 kg dry matter of sludge per year (68-109 g DS/capita.d) or about 800 kg wet sludge (95% water content) per year (2.2 L/capita.d) (Polprasert and Koottatep, 2017).

In Palestine, the specific sludge production in the West Bank, Gaza and over all are respectively 42, 32 and 37 g DS/capita.d (PWA, 2014). The specific wet sludge production in the West Bank, Gaza and over all are respectively 3.5, 0.55 and 1.92 L/ capita.d.

3.2.2. Secondary sludge (WAS) production rates

Secondary sludge production is a result of biological conversion of organic substrate into biomass. Typically, the Y_{actual} of heterotrophs is between 0.5-0.6 kg biomass/kg BOD biodegraded (Horan, 1990). However, in sewage treatment plants the secondary biomass production is higher due to the fact that (Veenstra, 2002):

- Nitrification is included in the system. The nitrifiers have substantially lower yield coefficients but contribute to overall biomass production.
- Remaining suspended solids from the incoming sewage do attach to biomass flocs thereby raising the total amount of dry solids accumulation within the aeration tank. This affects directly the excess sludge production rates. Sludge production rates may double to 0.8-1.2 kg TSS/kg BOD biodegraded.

The production rates of secondary biomass are also impacted by temperature. Temperature increase causes a rise in the endogenous respiration coefficient k_d. As a result, tropical countries often produce less secondary sludge than those with temperate temperatures (Popel, 1993). This may be the situation in the Arab countries, especially those in the Gulf and other hot region in other countries like Jordan and Palestine. For activated sludge systems with low F/M ratios or high sludge age, endogenous sludge respiration becomes more crucial. The absence of primary settling tanks and high SRT are connected with this so-called extended aeration mode of operation. This has a significant impact on the overall waste activated sludge production rates, which implies lower production rates of secondary sludge at lower F/M ratio.

The secondary sludge production due to biomass synthesis and adsorption of influent TSS can be stimulated by the TSS/BOD ratio of the sewage (Popel, 1993). The WAS production in activated sludge plants can simply be found in function of the operational F/M ratio. Typical WAS ranges between 0.4-1.2 kg TSS/$kgBOD_{removed}$ (Gray, 1990), assuming the use of primary sedimentation tanks prior to biological treatment. Regarding the WAS production in extended aeration systems, the influent solids may add up to the secondary sludge production due to the absence of primary settling. At higher F/M the specific sludge production increases.

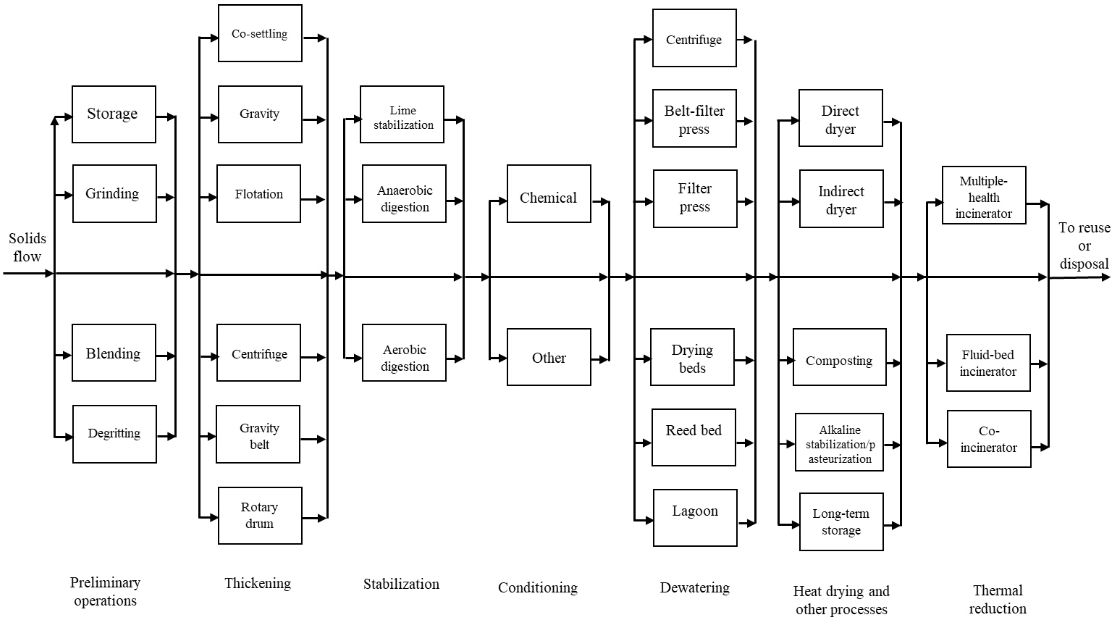
For trickling filters secondary sludge production rates are substantially lower. Due to the much higher solids, retention in the filter the biomass gest fairly stabilized (and is therefore commonly called “humus sludge”). Typical sludge production rates are 0.4-0.5 kg TSS/$kgBOD_{removed}$ for low loaded filters and 0.6-0.7 kg TSS for high loaded trickling filters (Veenstra, 2002).

3.3. Sludge treatment

3.3.1. Introduction

Increasingly wastewater treatment plants get problems with sludge handling and disposal. A generalized flow diagram incorporating the sludge unit operations and processes is presented in Figure 1. As shown almost an infinite number of combinations are possible (Metcalf and Eddy, 2003). The ultimate decision which sludge disposal method is to be applied depends on legislations and cost, including both capital and operation costs.

Figure 1. Alternative sludge flow diagrams for sludge treatment and disposal compose of a variety of available unit operations and processes (Metcalf and Eddy, 2003)



3.3.2. Sludge thickening

Sludge is concentrated or thickened to increase the dry solids content and achieve a considerable reduction in sludge volume. Lower sludge volume results in cost savings in further sludge processing and transportation to disposal sites.

Sludge thickening defined as the removal of water from the sludge to aim at a substantial reduction of the sludge volume. For example, if sludge with 0.8% DS can be thickened to 4% DS a fivefold decrease in sludge volume is achieved.

The major advantage of sludge thickening is the cost saving in downstream sludge handling processes. Stabilization as well as dewatering processes are improved at higher sludge concentrations. Common methods of sludge thickening are:

1. Gravity thickening
2. Flotation thickeners
3. Mechanical thickeners
4. Other methods (lagoons)

Mechanical thickening is becoming more important in those treatment plants where chemical or biological P removal is practiced (Veenstra, 2002).

Centrifuges exert excessive high centrifugal forces, which releases extra water from the sludge. At a low dry solids input the thickened sludge cake can reach a final content of 4 to 6% DS (without polymer addition) or 5 to 10 % with 2 to 8 kg polymer/ton DS added. Note that adding polymer is optional.

Rotary sieves or drums are operated at low rotational speed (5 to 25 rpm) around a horizontal axis and are commonly applied as pretreatment before sludge dewatering systems such as filter or belt presses. Rotary sieve drums include polymer conditioning of sludge prior to addition into a rotating cylinder with a screen. During rotation the separated water decants through the screen and the thickened sludge (3 – 4 % DS) rolls out at the end of the drum. With the addition of polymers the sludge can be concentrated from 0.5-2 % to 4-8% DS. The energy consumption is low compared to high-speed centrifuges.

Gravity belt thickeners: In particular, for sludge with a low dry solids content gravity thickening can provide in combination with sludge conditioning effective thickening.

3.3.3 Sludge stabilization

Stabilization processes make sludge less offensive (odor) as the organic matter content is reduced. There are biological (anaerobic and aerobic digestion) or physical-chemical (lime treatment) methods. A novel technology is wet air oxidation by the Vertech process (Veenstra, 2002).

Sludge stabilization is widely practiced at sewage treatment plants to reduce the potential odor formation due to the biodegradation of organic matter and to facilitate further sludge processing and disposal. The main aims of sludge stabilization processes are:

- To reduce pathogen contamination
- To eliminate the formation of offensive odors
- To improve subsequent sludge dewatering steps, and
- To reduce the amount of sludge solids to be disposed of.

Stabilization of sludge by chemical or heat methods is not commonly applied, as they are costly in terms of capital and operational cost. By chemical stabilization the high pH imposed on the sludge effectively reduce the microorganisms; no further biodegradation of organic matter can thus take place. As consequence of the high pH, NH_3 release may create local odor problems.

Lime can be added prior (pre-treatment) or after (post- treatment) sludge dewatering. Hydrated (slaked) lime ($Ca(OH)_2$) or quick lime (CaO) may be used (quick lime may help to increase the dry solids content of the sludge cake). Commonly slaked lime is used in dry form as it needs no water and creates no scaling problems in subsequent sludge dewatering units. Typical dosages are 100 to 500 kg $Ca(OH)_2$ per kg DS to maintain pH of around 12 for 30 minutes (Metcalf and Eddy, 2003).

The advantage of lime stabilization of dewatered sludge over biological stabilization methods is that the combination of exothermic chemical oxidation raises the temperature of the sludge to over 50 ^{o}C; this is combination with a pH 10, will effectively disinfect the sludge, and inactivate worm eggs.

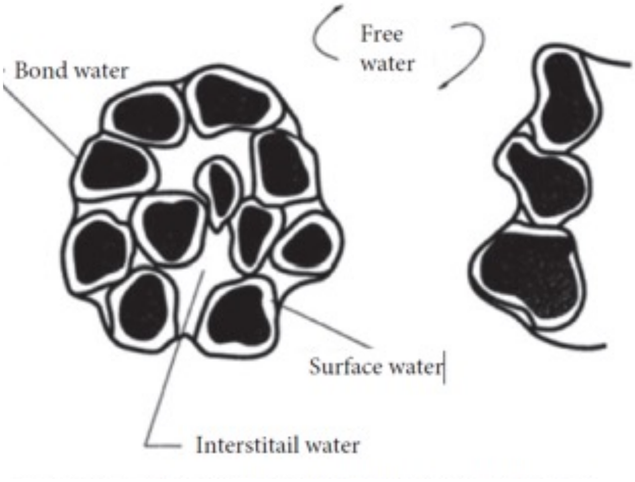
Anaerobic and aerobic sludge aims to stabilize organic materials in biologically, using aerobic or anaerobic bioreactors. Biological digestion processes are very effective in reducing the organic content of sludge, but they are not sufficient to produce sludge free of pathogens, and therefore further sludge treatment units are necessary later.

3.3.4. Sludge conditioning

Sludge conditioning is a pretreatment step to increase the efficiency of sludge thickening and dewatering capabilities of sludge. The two most common methods of sludge conditioning used are 1) addition of chemicals or 2) heat treatment (Veenstra, 2002).

Conditioning helps to release the different water fractions from the suspended and colloidal particles. Typically, four forms of water in sludge can be distinguished: free water, interstitial (capillary) water, surface water and bond water (Figure 2). Especially the removal of the last three water fractions from the sludge particles is very difficult and involves high-energy consumption.

Figure 2. The moisture distribution in sludge (Tsang and Vesilind, 1990)



Sludge conditioning is applied to improve sludge thickening or sludge dewatering processes. By chemical conditioning, inorganic Fe/AL salts or polymers are added to destabilize and agglomerate sludge particles into large flocs. Conditioning by heat treatment involves heating of the sludge under high pressure to break down the structure of the sludge particles and so to release the water fraction from the solids.

Chemical conditioning

In general, sludge particles have a colloidal nature; the particle is surrounded by an electrical charged double layer, which determines the thickening and dewaterability of sludges. The two main processes involved in conditioning are 1) the neutralization of the electrical charge of sludge particles and 2) the bridging of individual particles into a floc (Veenstra, 2002).

By coagulation with ferric chloride, lime or alum the sludge double layer is compressed and neutralized, the particles destabilize and water is more easily released from the sludge. This model works very well in water treatment sludges. However, for organic wastewater sludges the model does not explain observations from the field. Because of this deficiency the bridging model can be used to explain how different chemicals will flocculate biological sludges.

The basics of the chemical bridging model is that flocculates such as metal hydroxides and organic polyelectrolytes form long molecules that attract themselves to the sludge particles and draw them together, creating a strong flow structure necessary for efficient dewatering.

Dosages of the various conditioners to be applied in practice have to be found after analysis of the sludge by a variety of tests such as capillary suction time (CST), jar test, and modified filtration test (MFT). Chemicals used in sludge conditioning can be divided into (1) inorganic coagulants (Fe and Al salts and Ca(OH)2), and (2) organic polyelectrolytes or polymers containing some ionized groups.

Typical Fe/Al dosages applied range between 50 to 100 kg/ton DS. In case of Fe salts, additional lime dosages of 250 to 500 kg as Ca(OH)2 have to be added per ton DS to provide optimum pH (11.5) for particle bridging. Inorganic conditioners do increase the total sludge mass with 10 to 30%, lower the organic fraction and thus the incineration value of the dry solids, and reduce the potential application of sludge in agriculture due to the increased inorganic chemicals content. The other group of chemical conditioners are the organic polyelectrolytes or polymers. They mostly contain some ionized groups such as a carboxyl, amino, or other group. Polymers must perform the same two functions as the inorganic chemicals: charge neutralization and particle bridging. Cationic polymers are most commonly used in wastewater treatment as their positive charge matches to the negatively charged particles.

Polymer concentrations as low as 0.01-0.02 % (kg polymer/kg wet sludge) perform efficiently in sludge conditioning (Veenstra, 2002).

Organic polymers commonly replace Fe/Al salts in order to overcome the major problems involved with these inorganic chemicals. Advantages of organic chemicals over inorganic chemicals are:

- Dosages are around 10 times lower on dry sludge basis (typical dosages only 5-10 kg/ton DS).
- Polymers do not increase the residual inert fraction of sludge.

Polymers may also create problems such as:

- Clogging of dewatering filters
- Formation of gelatinous coating on mixers and pumps.

Conditioning by heat treatment

Heat treatment is conditioning process that involves heating of the sludge for short periods under pressure. By heat treatment, the structure of sludge flocs will be altered to liberate more water from the particles. The high capital cost of equipment limits its use to large treatment plants only (0.2m^3 per second) or facilities where space is limited (Veenstra, 2002).

3.3.5.Sludge dewatering

Dewatering processes reduce the water content of sludge to a level where they can be handles as solid matter rather than liquid. As a semisolid of sludge is better to handle for landfilling, agriculture use, incineration, heat drying and transportation. The solids content is raised to about 15-30% depending upon the type of dewatering method, the nature of the sludge and operational conditions. Usually, the disposal of sludge on landfills has to be paid for per ton of wet weight, so sludge dewatering is of crucial importance to reduce the ultimate disposal cost.

3.3.6. Drying and oxidation processes

These technologies include heat drying processes and sludge incineration.
Heat drying is used to reduce the water content of sludge to make it more suitable for incineration or for sale as fertilizer.
By incineration, the organic matter is combusted to produce an inert ash residue. Since the combustible portion of most sludge is below 75%, a substantial amount of ash remains for disposal (Veenstra, 2002).

Wet oxidation (Vertech system) involves wet oxidation of organic matter at high pressures with an additional supply of oxygen. The chemical reactions are usually carried out at temperatures above 200 °C. The equipment is highly sensitive to corrosion at these particular conditions of temperature, pressure, and dissolved oxygen levels.

3.4. Sludge disposal methods

Residual sludges (or ashes) can be disposed of on land or in water. Ultimate sludge disposal should not pollute the environment, should conserve its valuable resources and (reuse) and need to be economical. At the end, sludge always will result in a final disposal either as combustibles in the air, or as solids in the sea (sea outfalls) or on land. In many countries, the disposal of waste in the oceans is prohibited due to potential harmful effects on the aquatic environment. Sludge or residues are often dumped in a sanitary landfill where the wastes are covered periodically with a layer of soil. A landfill should be selected and designed in such a way to avoid drainage or leaching of pollutants into high quality water resources.

According to different treatment objectives, there are various sludge treatment technologies, which are used for simple disposal or valorization purpose (in term of nutrient and energy) (Ding *et al.*, 2021). Common methods include landfilling, composting, incineration, pyrolysis, anaerobic digestion, agricultural application and recycled as construction materials (Zhen *et al.*, 2017). Landfilling is the most widely used technology due to its simplicity and low cost of operation (Xiao *et al.*, 2021). In some developed regions, such as the EU, composting and anaerobic digestion are dominant sludge treatment technologies (Kelessidis and Stasinakis, 2012). In the United States, half of the sludge is used for agricultural application, with the remainder used in landfills and incineration (Raheem *et al.*, 2018). In China, the most common method is landfill (40%–50%), followed by vaporization, such as composting or recovered energy (Fang *et al.*, 2019). About 25% of sludge is recycled to make useful products, such as bricks, and 15% of the sludge is not properly disposed (Raheem *et al.*, 2018).

Stabilized sludge can be used as fertilizer or soil conditioner if micro-pollutant levels are not too high based on the regulations. Liquid sludge can be spread onto land by vacuum trucks. Disposal of sludge on agricultural land is acceptable although there are serious concerns about health hazards, such as pathogens and micro-pollutants. Properly handed in acceptable dosing rates however, sludge may represent a valuable resource for agricultural applications.

Composting of sludge offers another reuse option. Co-composting with domestic solid waste is most feasible, may reduce the final sludge volume with 50% and the end produce can recover part of the treatment cost per ton dry solids.

4. Socio-economic aspects

4.1. Use of sludge as low-cost input as fertilizer and/or soil conditioner

Bulk biosolids are frequently applied to farmland, forests, and reclamation sites in liquid or dewatered cake at forms at little or no cost to the landowner (Vesilind, 2003). Land application of biosolids to agricultural land within agricultural programs that involve growing of a variety of crops and animal production derive benefit from the components of biosolids and may involve crop and animal production that eventually become part of the food chain.

In an investigation conducted in Brazil on 2288 ha of agricultural land, 33,404 t of dry sludge was applied. Their findings indicated that the sludge supplemented 88% of the lime, 74% of the nitrogen, 73% of P2O5, and 35% of the K_2O needed for the growth of corn, soybean, bean, oat, and fruit trees. Farmers saved an average of $814/ha by using sludge (Bittencourt *et al.*, 2014).

Limited land areas and high sludge transportation and storage costs are two constraints that may restrict the land application of treated sludge. Therefore, taking into account the application of biosolids on agricultural land is necessary during the planning stage of the WWTP in order to include the availability of agricultural land nearby as one of the reasons for choosing the WWTP treatment site.

4.2. Social acceptability

It is important for engineers and operators to work together to develop several options for sludge and biosolids disposal, using the one that is of the greatest benefit at any time (Vesilind, 2003). The people who agree to accept the sludge products may change.

When evaluating sites with a view to eliminating areas potentially unsuitable for land application, the criteria may preclude culturally sensitive lands such as old cemeteries and burial grounds, as well as public recreational areas (Vesilind, 2003).

Although using sludge in farming is a popular practice in many low-income nations, farmers from diverse cultures may or may not embrace it due to its anthropogenic origin, the general opinion that sewage is obnoxious and its offensive smell (Keraita *et al.*, 2008). Therefore, it is essential to look at how farmers perceive and act when applying sludge to the soil.

Through a survey, Nassar *et al.* (2009) investigated the farmers' acceptance and willingness to utilize treated sludge as a substitute for organic fertilizers in the Gaza Strip. The findings showed that: (a) the scarcity and high cost of organic fertilizers could encourage farmers to use treated sludge if sufficient amounts of treated sludge are available when needed; (b) farmers who have never used treated sludge may be willing to use sludge if it is well treated, its application shows good results, and it is safe to handle; and (c) the majority of farmers prefer to use sludge for fertilizing trees and field crops rather than growing all types of crops.

In the northern Gaza Strip, sludge has not been used in agriculture for a number of reasons, according to Yassin and Abed Rabou (2002), including the following: (a) sludge is viewed as a spiritually polluting substance; (b) sludge may harm crops; and (c) sludge contains pathogens, attracts insects, and emits odors. However, their research showed that farmers' usage of sludge might be influenced by the availability of cheap, safe, and beneficial sludge. The farmers' willingness to pay for sludge depends on its quality and safety for its application.

The findings of a research by Krogmann *et al*. (2000) on farmers' worries about applying biosolids on their crops showed that the farmers were more worried about the conditions of their land and were less concerned about the environmental and health problems that sludge may provide.

4.3. Incentives of sludge reuse

Bulk biosolids are frequently applied to farmland, forests, and reclamation sites in liquid or dewatered cake at little or no cost to the landowner (Vesilind, 2003). In spite of negative prejudices, farmers recognized the advantages and disadvantages of employing sludge, according to a research by Krogmann *et al.* (2000). The farmers understood that adding sludge to the soil could improve its properties by adding organic matter, and possibly increases crop yields.

Chen *et al*. (2022) reported that according to the priority of stakeholders in wastewater management sector, the sludge could be valorized as nutrient and material, which will substitute alternative products and increase the resource utilization.

Treated sludge application to agricultural land is a viable option for final sludge disposal. Many WWTP operators confront continuous challenge to find proper place to dispose the wasted sludge. Even when sludge is disposed of in solid waste landfills, transporting the sludge is usually very expensive and requires very low water content in order to avoid operational problems in the landfill.

4.4. Obstacles of sludge reuse

Sludge application on agricultural land is a sensitive issue. A number of factors, such as aesthetic and socio-economic considerations, cultural, religious, and health concerns, as well as a lack of information, affect the acceptance of using sludge. Sometimes the market accepts the valorized products poorly. Sometimes, the valorized products have a low market acceptance (Zhang *et al*., 2016). The poor sludge characteristics are a major barrier to biosolids recycling on agricultural land. Particularly, the high levels of heavy metals (Feng *et al*., 2018) might severely restrict a safe land application of the sludge. The disposal of industrial wastewater into the municipal public sewers is an important reason for the high metal contents in sludge.

Objectionable odor of the sludge could result in reduced public acceptance of land application options. Therefore, all sludge management systems need to consider objectionable odor as a potential problem (Polprasert and Koottatep, 2017).

Lacking national standards and obligatory technical requirements for sludge disposal also contribute to the low biosolids recycling rates (Lu, 2019). Reuse projects, even those that are technically and financially well designed, might fail if planners do not sufficiently take into account the dynamics of societal acceptance (Drechsel *et al*., 2015).

In two agricultural communities in the West Bank of Palestine, namely the villages of Anza and Beit Dajan, Rashid *et al*. (2017) investigated the farmers' perceptions on land application of treated sewage sludge. When asked which factors would influence whether or not farmers decided to use sewage sludge on their farms, 38% of the farmers selected "consumers' acceptance to buy crops fertilized by sludge," 22% selected "price of sludge," 16% selected "sludge meets the public health requirements," and 4% selected "religious reasons." The remaining 20% of the farmers said that all four of the aforementioned variables when making a decision influence them. In this study, 45% of the farmers believed that the application of treated sludge to land should be carried out in a manner that protects the environment, the economy, and human health.

5. Regulatory framework

5.1. Laws, regulations, adopted standards

In conjunction with the trend toward beneficial use of wastewater solids compared with disposal, the design of any sludge or biosolids project should take into account the quality of the sludge to be disposed of and the prevailing regulations (Vesilind, 2003).

In most cases, the selection of both sludge treatment and biosolids disposal is governed by disposal regulations. For instance, the regulation governing sludge disposal in the United States is the 40 CFR 503 regulations promulgated by the U.S. environmental Protection Agency (U.S. EPA) (see section 7.2).

In Palestine, sludge application for agricultural purposes is allowed. The process is regulated, in addition to the Palestinian Environmental law, in two main documents (1) Obligatory Technical Instructions No. 59 for year 2015 and "Use of treated sludge and Sludge disposal" standards. The Palestinian regulations set values for the maximum concentration of heavy metals in soil, sludge and the maximum limits for sludge applied to agricultural land based on a yearly rate.

According to the Palestinian regulations, treated sludge can be applied to agricultural land planted with fruit trees, and field crops and pastures, and do not allow the use of treated sludge to fertilize planted land with vegetables, as well as parks and home gardens and green spaces from nearby communities and sites frequented by the public. Also not allowed for use in fertilizing planted land with crops radical as radishes, carrots, potatoes and other, whether eaten raw or cooked (MoA and PWA, 2015; PSI, 2010; EQA, 2000).

According to the Jordanian Standard (JS 1145-2006), sludge is classified into three types (i.e., types I, II, and III) based on heavy metal content and level of treatment necessary to reduce the pathogen content. Both type I and II sludge can be used for agriculture (i.e., as soil amendment); however, type II can only be used as a soil amendment during land preparation in areas not accessible to the public (i.e., public parks). Type III sludge is permitted to be landfilled, in addition to type I and II sludge (JS, 2006).

5.2. Stakeholders' roles

Several stakeholders at different levels are involved in the management of sewage facilities. The stakeholders include entities at the national level. The water authorities are usually the national bodies responsible for policy, planning and monitoring of water-related service delivery including monitoring effluent quality. They might also be responsible for future upgrades of the plant, based on the ownership of the wastewater treatment plant, as in some cases the municipalities are the owners of the wastewater treatment plant.

Stakeholders also include the day-to-day operators of the WWTP. While issues related to agricultural irrigation water and the use of biosolids in agriculture often fall under the responsibility of ministries of agriculture, who issue licenses to allow farmers to use recycled water and biosolids from wastewater treatment plants. They also monitor the quality of biosolids used for agricultural lands, while the quality of marketed crops produced is monitored jointly by the Ministries of Health, National Economy and Agriculture. Farmers and farmer unions are major stakeholders in the use of treated sludge, as are consumers. However, the nature of roles, distribution of responsibilities and relationships between various stakeholders may differ from one country to another.

In terms of relationships between the various stakeholders, in terms of role of each stakeholder and the relationship between them, vary from country to country.

6. Environmental impact

6.1. Soil structure and quality

When added to soil, sewage sludge serves as a source of plant nutrients and a useful soil amendment. Sludge applied to land provides organic matter to improve soil structure (greater aeration and water holding capacity), main plant nutrients (N, P, K), and micro-plant nutrients (Zn, Fe, and Cu). The characteristics of the soil to which it is applied, the plant species to be grown, and the composition of the sludge all affect how effective it is at improving soil.

Organic matters in sludge can improve physical properties of soil, namely, soil's ability to absorb and store moisture (EC, 2001; Sripanomtanakorn and Polprasert 2001; U.S. EPA, 2023). Over time, the use of farmland can result in the depletion of organic matter in soil. Because sludge can replenish organic matter in soil and add nutrients at least partially in soil, the use of sludge can reduce the costs of crop production. Treated sewage sludge is considerably less expensive than the fertilizers manufactured in a chemical plant. In the European farming communities, over 30% of sewage sludge is being used as fertilizer (Wang *et al*., 2008). The positive aspects of sludge as a fertilizer and soil amendment have created the high sludge demand (Pritchard *et al*., 2010).

6.2. Sludge application impact on water resources

The contamination of water supplies with heavy metals, nitrogenous chemicals, and pathogens is among the key issues of applying sludge to land. Regulations that set limitations on application rates and concentrations for pathogens and heavy metals restrict pollutants. The focus of sludge application rates in agriculture is primarily on the nutrients required for crops than on heavy metals in countries with separate sewerage systems and where industrial discharges into sewer system is appropriately pre-treated or isolated from the municipal sewer. To prevent major eutrophication of surface water and water resources, N or P restrictions are crucial.

Particularly, nitrogen can contaminate shallow groundwater aquifers when it permeates soil strata. According to reports, excessive fertilizer application rates to agriculture are to blame for high nitrate levels. It is difficult to determine the proper sludge application rates on land based on the rate at which crops uptake nutrients. They should consider how nutrient uptake rates vary depending on the season, the species, and how much organic nitrogen is mineralized. In fact, agricultural activities require nutrients, whether in the form of commercial nutrients, biosolids, or other, and consequently might pollute water sources with nutrients in a manner that is not precisely tied to the application of sludge to agricultural lands.

6.3. Use of sludge vs. climate change

The high-energy demand and direct emissions in WWTPs lead to significant GHG emissions. For instance, the electricity consumption by WWTPs in China accounts for approximately 1% of national electricity consumption (Zhang *et al.*, 2021), where for different treatment systems, the GHG intensities of WWTPs range from 0.268 to 0.738 kgCO_2-eq./m^3. The rapid development of WWTP also leads to a sharp increase in sewage sludge generation (Lu *et al.*, 2019; Zhang *et al.*, 2017). According to published studies, sludge management contributes approximately 50% of the overall GHG from wastewater treatment plants (Zhao *et al.*, 2022).

According to different treatment objectives, there are various sludge treatment technologies, which are used for simple disposal or valorization purpose (in term of nutrient and energy) (Ding *et al.*, 2021). Landfilling is the most widely used technology due to its simplicity and low cost of operation (Xiao *et al.*, 2021). With the foreseeable stricter environmental standard and waste management policies in several countries, like China, such as “zero-waste cities”, landfilling sludge is expected to be restricted in the near future. More efficient sludge treatment systems can improve eco-efficiency of wastewater treatment plants through resource recovery and offsetting corresponding environmental impacts, such GHG emissions (Ding *et al.*, 2021).

The life cycle GHG emissions of processing 1 ton of dry sludge with different treatment systems were researched by Chen *et al.* (2022). Most of sludge treatment systems, including material valorization, conventional disposal, nutrient recovery and energy recovery have positive values in GHG emissions. For composting group, the nitrogen and phosphorous in sludge can be recovered as fertilizer, which can improve the resource usage efficiency and avoided fertilizer production. The GHG emissions (especially CH_4, N_2O) generated during composting can offset the carbon credit from fertilizer substitution (Piippo *et al.*, 2018; Righi *et al.*, 2013). Indeed, the use of biosolids as a supplementary source of nitrogen has a positive impact on reducing GHG by reducing the use of CO_2-heavy nitrogen commercial fertilizers.

The total GHG emissions of sludge composting mainly range from 0 to 1 ton of CO2 per one ton of dry sludge treated. For conventional disposal and material valorization group, some systems may achieve GHG mitigation effect. The most sustainable method for treating sewage sludge depends strongly on the situation and local circumstances, like population density, temperature, and distance of transport (Piippo *et al.*, 2018). For instance, Righi *et al.* (2013) reported that the anaerobic co-digestion of dewatered sewage sludge and organic fraction of municipal solid waste (OFMSW) in small plants combined with composting post-treatment might offer an environmentally sustainable option of waste management in small communities. This is achieved by (1) a strong reduction in the distances and volumes transported by road, (2) low energy requirement for the process itself, (3) energy saving from CHP unit and (4) energy/resources saving from the compost produced by the digested matter.

Bulk biosolids shall not be applied if likely to adversely affect a threatened or endangered species (Vesilind, 2003).

7. Health aspects

7.1. Health concerns

The two most important characteristics of sludge that limits its use are the heavy metals and the pathogens. Because of the continuing concern with sludge disposal, many farmers are insisting on accepting only Class A sludge (Vesilind, 2003). Bulk biosolids are frequently applied to farmland, forests and reclamation sites in liquid or dewatered cake forms. As a minimum, these materials need to meet the pollutant ceiling concentrations, Class B pathogen reduction requirements, and vector attraction reduction requirements and should be applied using the cumulative pollutant loading rates if they do not meet the pollutant concentration limits. The sewage sludge applied to agricultural areas can cause adverse ecological and health risks. This is mainly associated with the accumulation of toxic heavy metals such as Zn, Cu, Cr, Cd, and Pb in the soil that reach the food plants (Martinez and Motto, 2020).

In a study of land application of sludge in Bangkok, Thailand, Pasda *et al*. (2005) reported the presence of heavy metals and fecal coliforms in sludge. They suggested that sludge should be heated by composting to reduce pathogen population.

Despite the increasing use of sewage sludge, there are major drawbacks, as follows: (a) potential presence of heavy metals, organic pollutants, and pathogens, which can accumulate in sludge (Wang 1997); and (b) offensive odors produced by sludge. These drawbacks pose public health and environmental issues (National Academy of Sciences 1996). The disadvantages, however, can be minimized by choosing suitable crops, adopting proper sludge spreading techniques, and regulating the time between sludge applications and harvesting (Dahlstrom 2005).

7.2. International standards and guidelines on safe sludge reuse

In the United States, regulations (40 CFR Part 503) were promulgated in 1993 by the U.S Environmental Protection Agency that established pollutant numerical limits and management practices for the reuse and disposal of solids generated from the processing of municipal wastewater. The regulations were designed to protect public health and the environment from the reasonably anticipated adverse effects of pollutants contained in biosolids.

The regulations addressed by 40 CFR Part 503 included land application of biosolids. Land application relates to biosolids reuse and includes all forms of applying bulk or bagged biosolids to land for beneficial uses at agronomic rates, i.e., rates designed to provide the amount of nitrogen needed y crops or vegetation while minimizing the amount that passes below the root zone. The regulations established (1) two levels of biosolids quality with respect to heavy metals concentrations – pollutant ceiling and pollutants concentrations ("high" quality biosolids); (2) two levels of quality with respect to pathogen densities – Class A and Class B; and (3) two types of approaches for meeting vector attraction –biosolids processing or use of physical barriers. Vector attraction reduction decreases the potential for spreading infectious disease by vectors such as rodents, insects, and birds.

The 40 CFR Part 503 regulations divide the quality of biosolids into two categories, referred to as Class A and Class B. Class A biosolids need to meet specific criteria to ensure they are safe to be used by the public and for nurseries, gardens, and golf courses. Class B biosolids have lesser treatment requirements than Class A, and typically are used for application to agricultural land or disposed of in a landfill.

When biosolids are prepared for sale or given away for land application to lawns and home gardens or are marketed in containers, Class A biosolids need to meet one of the following criteria:

1. A fecal coliform density of less than 1000 most probable number (MPN)/ g total dry solids, or
2. A salmonella sp. Density of less than 3 MPN per 4 g total dry solids.

   In addition, the requirements of one of the following pathogen reduction alternatives are necessary to be met (Vesilind, 2003; Metcalf and Eddy, 2003):

- Thermally treated biosolids: use one of four-time temperature regimes. An increased temperature should be maintained for a prescribed period according to the guidelines listed in Table Alkaline treatment: biosolids treated in a high pH-high temperature process; specific pH, temperature and air-drying requirements (pH>12 for at least 72 hours; during this time, the temperature of the biosolids should be greater than 52 °C for at least 12 hours; after the 72-hour period, the biosolids should be air dried to at least 12 hours).
- For biosolids treated in other processes: demonstrate that the process can reduce enteric viruses and viable helminth ova. Maintain operating conditions used in the demonstration.
- Biosolids treated in unknown processes: demonstration of the process is unnecessary. Instead, test for pathogens – Salmonella sp. bacteria, enteric viruses, and viable helminth ova-at the time the biosolids are used or disposed of or are prepared for sale or giveaway in a bag or other container for application to the land, or when prepared to meet the requirements in 503.10(b), (c), (e) or (f)
- Biosolids have been treated by processes to further remove pathogens (PFRP) or equivalent processes, as determined by the permitting authority.

Table 5. The four time-temperature regimes for class A pathogen reduction under alternative 1 (Vesilind, 2003)

Total solids	Temperature (*t*)	Time (d)	Equation	Notes
≥7%	≥50 °C	≥20 min		No heating of small particles by warmed gases or immersible liquid
≥7%	≥50 °C	>15 sec		Small particles heated by warmed gases or immersible liquid
<7%	>50 °C	≥15 sec to <30 min		
<7%	≥50 °C	≥30 min		

To be land applied, biosolids need to meet the pollutant ceiling concentrations and cumulative pollutant loading rates or pollutant concentration limits. Bulk biosolids applied to lawns and home gardens need to meet the pollutant concentration limits. Biosolids sold or given away in bags or other containers need to meet the pollutant concentration limits or the pollutant ceiling concentrations and be applied at an annual product application rate that is based on the annual pollutant loading rates. Under the federal 503 rules, certain site restrictions apply to Class B use, but no individual site permits are required for its use. The federal regulations also establish standards for nine contaminants (Table 6).

The standards include so-called 'exceptional quality' (EQ) sludges, which meet certain concentration limits (no more than X parts per million of any of the nine regulated contaminants) as well as pathogen and vector reduction requirements. With regard to metal concentrations, sludges and sludge products that fail to meet one or more of those 'EQ' pollutant concentrations, but which fall below a higher ceiling concentration may be applied, but the applicator is directed to keep track of the total amount of each metal applied and cease application when a regulatory cumulative pollutant-loading limit is reached.

Sludge products that fail to meet one or more of the 'EQ' pollutant concentrations, but which fall below the ceiling concentration may still be distributed to homes or in bags as long as information on the acceptable annual pollutant-loading rate is provided to the user. In this context, there are many voices in the U.S., which support that although the standards have been developed through extensive risk assessment studies, however data gaps and non-protective policy choices result in regulations that are not adequately protective of human health and the environment (Harrison *et al.*, 1999; Vesilind, 2003; Doula, 2017).

Table 6. Land application pollutant limits (dry-weight basis) in U.S. EPA Part 503 regulations (Doula, 2017)

Pollutant	[1]Pollutant concentration in EQ biosolids (mg/kg)	[2]Ceiling concentration in biosolids applied to land (mg/kg)	[3]Cumulative pollutant loading rate limits (kg/ha)	Annual pollutant loading rates, kg/ha.yr
Arsenic	41	75	41	2.0
Cadmium	39	85	39	1.9
Copper	1500	4300	1500	75
Lead	300	840	300	15
Mercury	17	57	17	0.85
Molybdenum	-	75	-	-
Nickel	420	420	420	21
Selenium	100	100	100	5.0
Zinc	2800	7500	2800	140

1: Applies to bulk biosolids & bagged biosolids; 2: Applies to all biosolids that are land-applied; 3: Applies to bulk non-EQ biosolids; 4: Applies to bagged biosolids not meeting EQ limits.

The European Union (EU), which comprises 27 independent member states, is further divided into EU 15, consisting of 15 member states, and EU 12, consisting of 12 member states. These member states are required to enact EU Regulations and Directives into their own national legislations. Sludge management Directives: legislative tools, acts, and directives have regulated sludge management in EU countries, during the last 30 years, directly and indirectly by. Among them, Directive 86/278/EEC (adopted in 1986) and Directive 91/271/EEC (adopted in 1991) have the most significant impact.

Directive 86/278/EEC sets rules on how farmers can use sewage sludge as a fertilizer to prevent it from harming the soil, vegetation, animals, and human health without compromising the quality of the soil or surface water and groundwater. It sets specific limits on the concentrations of seven heavy metals allowed in soil that may be toxic to plants and humans. Since the adoption of this Directive, many member states have enacted and implemented stricter limit values for heavy metals and other contaminants (European Communities Commission 1986). Due to the implementation of Directive 91/271/EEC, known as Urban Wastewater Treatment Directive, the quantity of sludge requiring disposal has increased and the quality of sludge has substantially improved in the EU 15 states during 2000–2010. This Directive bans the disposal of sludge at sea (by December 31, 1998), resulting in two options for sludge management, recycling to agricultural land or disposal to landfill (Inglezakis *et al.*, 2011a, b).

8. Management of bio-solids application on agricultural land

8.1. Plant available nutrients in bio-solids

Sewage sludge when applied to soils provides a source of plant nutrients and it is an effective amendment, Sludge applied to land provides major plant nutrients such as N, P, K; micro-plant nutrients such as Cu, Fe, and Zn; and organic matter for improving the soil structure (e.g., better aeration and water holding capacity). Some of the limitations in using sludge as fertilizer include the fluctuation of nutrient content, and N, P and K levels are about one-fifth of those found in typical chemical fertilizer. Much of the N and P in sludge are in organic combination that should be mineralized before becoming available to plants. The rate of mineralization for N and P in soil is dependent upon local conditions such as soil type, temperature, soil pH, soil water and other soil chemical and physical characteristics (Polprasert and Koottatep, 2017).

Typical nutrient values of wastewater biosolids as compared to commercial fertilizers are reported in Table 7. Sludge utilization is a supplement or replacement of commercial fertilizers. In most of the land application systems, biosolids provide sufficient nutrients for good plant growth. In some land application systems, the phosphorous and potassium content may be low and require amendments (Metcalf and Eddy, 2003).

Table 7. Comparison of nutrient levels in commercial fertilizers and wastewater biosolids[a]

Product	Nutrients, %		
	Nitrogen	Phosphorous	Potassium
Fertilizers for typical agricultural use a	5	10	10
Typical values for stabilized wastewater biosolids (based on TS)	3.3	2.3	0.3

[a] The concentrations of nutrients may vary widely depending upon the soil crop needs.

Source: Metcalf and Eddy (2003)

8.2. Transport and storage

Table 8 shows the various methods to handle and transport sludge from a source to land application/disposal site. Transportation may be accomplished by pipeline (gravity flow or pressured), tank truck, barge, or conveyor rail. Sludge characteristics (e.g., solid contents), sludge volume, elevation differences, transport distance and land availability are important factors in selecting a method of sludge transportation. Liquid sludge (1-10% solid contents) is generally suitable for any mode of sludge transport, while only trucks or rail hopper cars should transport semi-solid or solid sludge, having high solid content (8-80%). Tank trucks are currently widely used to transport and apply sludge on land because they afford flexibility in the selection of land application sites. Usually, a storage facility for sludge is provided at the land application site.

Table 8. Sludge solids content and handling characteristics

Type	Solid contents (%)	Handling methods
Liquid	1-10	Gravity flow, pump, tank support
Semi-solid ('wet' solid)	8-30	Conveyor, auger, truck transport (water tight box)
Solid ('dry' solid)	25-80	Conveyor, bucket, truck transport

Knezek and Miller (1978) reported in Polprasert and Koottatep (2017)

8.3. Best practice

Mateo-Sagasta *et al.* (2022) made the argument that someone who has previously opposed the idea of using treated wastewater may alter his mind if someone with comparable cultural values supports the reuse. A good practice is a real-world case study that consistently demonstrates superior results than competing approaches (Mannina *et al.*, 2022). Establishing demonstration locations for the use of biosolids in agriculture is a very useful tool to stimulate farmers' acceptance of waste recycling.

According to Righi *et al.* (2013), dewatered sewage sludge and OFMSW anaerobic co-digestion in small plants along with composting post-treatment may provide an environmentally sustainable option for waste management.

8.4. Capacity development

According to the regulations, farmers are required to recognize the quantity of nutrients in sludge, record the amount of sludge added to their lands, and the amount of heavy metals. It is essential that farmers are aware of the nutrients that their growing crops demand. The farmers should be able to determine the necessary amounts if additional chemical fertilizers are to be added in addition to the biosolids. It is advised to conduct awareness campaigns to educate and train farmers for the safe and efficient use of sludge in order to encourage land application of sludge. The capacity building activates should also include other stakeholders, specifically extensions services, decisions makers, etc. A broader vision of capacity building as an inclusive participatory program including farmers, private sector, line ministries officer (agriculture, water, environment, health, planning, etc. need to be considered.

8.5. Role of research and development,

In case other processes are used to treat the sludge to meet the Class A requirements, other than those reported in section 7.1, then it is crucial that the enteric viruses and viable helminth ova should be monitored to prove that the results are consistent with the values or ranges of values documented all time. For instance, quality of sludge dried by drying beds in hot climate countries, or countries, or regions within the same country, with seasonal and/or geographic big variation of temperature, like for instance the case in Jericho/Palestine which is very hot during summer and hotter than other parts of the West Bank.

It is important to conduct opinion surveys on the social acceptance of agricultural products fertilized with biosolids.

Data on the yield of crops, the amount of biosolids utilized, the amount of chemical fertilizer used, economic analysis, soil quality, and an investigation of how these aspects affect farmers' acceptance should be made available for the farms that receive biosolids. To fully understand the risk of contaminants of emergent concern (CEC) present in wastewater, it is also important to quantify and identify pollutants of concern in soils and crops (Garduo-Jiménez *et al*., 2023). Life cycle environmental impacts of biosolids use should be carried out. The possible impacts of sludge on the farmland and the environment should be monitored continuously by conducting laboratory testing. Research needs to be conducted addressing farmers' concerns about land application of sludge, before and after applying sludge on their farmlands. The farmers and the general public need to be provided with access to information, and the research results should be communicated with them.

It is necessary that the decision makers include the subject of biosolids application to agricultural land among the national research priorities. The biosolids land application projects need to have research components to assure the optimal socio-economic and environmental benefits, and to document the lessons learnt. Financing research, by link between research and extension services is crucial to mitigate the challenges and to have more insight in the sustainable land application of biomass.

9. Conclusions and possible directions

9.1. Conclusions

This study demonstrates that applying treated sludge, also known as biosolids, is a very sensible and appealing choice for long-term sludge management. This is due to the fact that the land application of treated sludge (1) provides a final disposal option for the continuously growing amount of sludge produced as a waste by-product of wastewater treatment plants, and (2) recycles nutrients and organic matter that are very beneficial for agricultural land, increasing farmland productivity and decreasing the cost of commercial fertilizers, both of which are beneficial for the environment. The nitrogen content of the treated sludge serves as a supplementary source of nitrogen for crops, reducing the need for energy-intensive chemical fertilizers through resource recovery and decreasing the environmental impact of GHG emissions by reducing the use of CO_2-heavy commercial nitrogen fertilizers in particular.

Sludge should be treated in the wastewater treatment plant using the appropriate technologies and processes in order to achieve the required sludge quality. Every country ought to have National Obligatory Technical Requirements and Standards available. Emphasis needs to be given to control of industrial wastewater discharge in the sewerage system so to assure no excessive pollution with heavy metals.

Despite the obvious advantages of applying biosolids to agricultural land, there are a number of socio-economic, cultural, and environmental issues that pose obstacles to the effective use of treated sludge. These concerns have to be taken into account before to, during, and following the application of sludge to farmlands. This is essential to ensure that sewage sludge is disposed of securely and with the least possible harm to the environment and human health.

9.2. Possible directions

Possible directions for proceeding with successful land application of treated sludge are proposed as follow:

- Integrated pilot projects of biosolids application on agricultural lands including dimensions related to crops quality, soil quality, sludge quantification and characterization, social acceptance, environmental impact, stakeholders' engagement.
- The authorities are advised to ensure the proper control of industrial discharges in the public sewerage system so to assure that no harmful substances, like heavy metals, are disposed.
- Capacity development targeting different stakeholders, from decision makers to farmers, on methods, processes, regulations, and instruments for monitoring and evaluation of safe use of sludge in agriculture.

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