Food and Agriculture Organization of the United Nations

A REVIEW OF POTENTIAL AND LIMITATIONS OF DREDGED SEDIMENT APPLICATION IN AGRICULTURE

A review of potential and limitations of dredged sediment application in agriculture

Authors

Elias Fereres, Margarita García Vila, Angel Gonzalez-Gomez
University of Córdoba

Maher Salman, Eva Pek, Camilla Simongini, Youssef Bizri and Nour El-Korek
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The report was prepared by Elias Fereres, University of Cordoba, Spain; Margarita García Vila, University of Cordoba, Spain; and Angel Gonzalez-Gomez, University of Cordoba, Spain; and FAO team led by Maher Salman, Senior Land and Water Officer & Leader of the Irrigation and Water Resources Management Team, Land and Water Division (NSL); and including Eva Pek, Land and Water Officer (NSL), Camilla Simongini, Environmental Engineering Specialist (NSL), Youssef Bizri, Project Manager (FAO-Lebanon), and Nour El-Korek, Irrigation Water Management Specialist (FAO-Lebanon).

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Abbreviations and acronyms

EC	European Commission
EEC	European Economic Community
FAO	Food and Agriculture Organization of the United Nations
ISO	International Organization for Standardization
MPN	Most probable number
MSW	Municipal solid waste
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commission for Refugees
USEPA	United States Environmental Protection Agency
WWTPs	Sludge from wastewater treatment plants

Units

°C	degree Celsius
cm	centimetre
ha	hectare
l	litre
l/s	litre per second
m	metre
m^3	cubic metre
mg/kg	milligram per kilogram
mg/l	milligrams per litre
ml	millilitre
tonne/ha	tonne per hectare
µm	micrometre


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SECTION 1

INTRODUCTION

The alarming trend of urbanization is stretching natural resources and leading to an environmental degradation in many regions. Nowhere are the impacts more evident than in water-scarce regions where the already limited resources are often managed unsustainably. The loss of ecosystem functions has cascading effects on the health of the environment, the restoration capacity and eventually affects its resilience. Urbanization and population density is a major threat for the Mediterranean region, where urban pressure increased by 75 percent between 1965 and 2015 (UNEP – Mediterranean Action Plan, 2020). The coastal area of Lebanon is no exception to the rapid environmental degradation, as the coastline hosts 70 percent of the Lebanese population (International Union for Conservation of Nature and Ministry of Environment, 2021). Furthermore, the southernmost and northernmost parts of the coast are occupied with high-potential agricultural areas (Ministry of Environment and UNDP, 2011).

The Governorate of Akkar, in the north of Lebanon clearly demonstrates the far-reaching consequences of urbanization-induced ecosystem degradation. There has been a recent sharp population increase due to migration that adds to the pre-existing vulnerabilities of the area (UNHCR, 2015). The challenges are compounded by a range of further risks, such as food and water insecurity, unsustainable intensification of agriculture and industry, changing consumption patterns, all under the threat of climate change. These challenges place a heavy strain on both fresh and marine water resources. One of the impacts of the multiple crises is the inability to handle waste by the existing public infrastructures. This has entailed the accumulation of solid urban waste in irrigation canals and has led to the pollution of water resources. The adverse effects of contamination are further exacerbated by the sediment deposited on the canal bottoms, which also carry a large amount of pollutants. Sediment that may be considered a valuable source of soil amendment, thus, becomes the vehicle of pollutant transport.

Despite the importance of irrigated agriculture in Akkar, the irrigation infrastructure is neither efficient nor resilient to withstand the growing pressures. A sterling example of the outdated practices of agricultural water resource management is the manual sediment removal. The proper disposal of dredged sediment is of critical importance, as it may be severely contaminated by pollutants, including heavy metals and pathogens. As irrigation canals pass through highly populated and industrial areas, management options must set out optimal strategies to make the best use of the sediment without posing threats for the environment and human habitats.

The review report provides an insight into sediment collection and use strategies that can be transferred to El-Bared irrigation system. The report is the outcome of the project "Rehabilitation and waste management of the El-Bared Canal Irrigation System", financed by the Government of Norway. The report aims to provide technical guidelines in support of the development of sediment management strategies in the north of Lebanon. In the specific, it aims at providing an overview of global and national practices of sediment application; setting the theoretical baseline for the implementation of these practices; and paving the way for scalable pilots in the country. The report contributes to the higher objectives of the country's commitment to protect marine resources of the Mediterranean Sea, under the Barcelona Convention.

The available literature on sediment reuse from irrigation canals is scarce, yet some studies discussing sediment from lakes and urban water infrastructure can be found. Therefore, the review draws conclusions from such studies. Due to the similarity between sewage sludge and sediment contaminated by human activities, some sections use these terms interchangeably. The review also synthetizes a broad range of information sources which includes scientific papers, technical reports, and manuals. It is structured in five interrelated sections:

- sediment generation and management options;
- potential use and limitations of sludge and dredged sediments in agriculture;
- regulatory framework for the use of sludge and contaminated sediment;
- common protocols for the analysis of sludge characteristics; and
- global case studies demonstrating sediments reuse in crop production.

In the first section, a brief overview is presented to introduce the process of sediment generation, together with the traditional and more innovative ways of managing municipal solid waste (MSW) and sludge from wastewater treatment plants (WWTPs). The second section deals with the pros and cons of the application of sludge and sediments to the soil and crops. The third section summarizes the general international guidelines for the use of sludge and presents the current regulatory framework in Lebanon. The typical indicators for the quality assessment of sludge or MSW before its use as a soil amendment are presented in the fourth section, and complementary information on the measurement protocols is provided. The fifth section discusses successful case studies, involving the use of WWTPs sludge as a component in the manufacture of chemical fertilizer and the application of lake-dredged sediments to pasture lands. The report, then, summarizes the key messages to be considered in the case of El-Bared irrigation system, and outlines the next steps for the set-up of location-specific pilots.

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SECTION 2

SEDIMENT GENERATION AND MANAGEMENT OPTIONS

Rationale for sediment management

The sediment in irrigation canals is generated mostly by upstream erosion, but high runoff, particle transport by wind, human and industrial pollution can also increase the rate of sedimentation. Depending on the dredging methods and the features of the surrounding environment, sediment is composed by a diverse set of particles with different physical-chemical properties, microbial communities, and pollutant types and loads (Renella, 2021).

Sediments are usually made of soil particles of different sizes and some organic matter. FAO (1996) suggests the use of sediment delivery ratio to define to what extent the eroded soil is stored within the basin. The sediment delivery ratio measures the proportion of sediment yield and gross erosion in the basin. Another equally important indicator, namely the sediment loss, is calculated from the parameters of rainfall energy factor, soil erodibility factor, slope-length factor, cropping management factor and erosion-control practice factor (FAO, 1996).

While the effect of the factors on the soil loss can be calculated through a simple formula, the data acquisition to estimate the value of the factors is complex and often requires long-term observations. If a less comprehensive and more piecemeal view of the sedimentation rate is required, different formulae exist to conduct a context-specific analysis. There are an ample number of calculation methods to model the sedimentation rates of flow even in data scarce environment. Another approach is the direct observation when the thickness and composition of the sediment deposit is observed over time.

Box 1. **Definitions**

The report uses the definitions of sediment and sewage sludge in tandem. Public irrigation schemes, particularly the peri-urban public schemes, are exposed to different sources of pollution such as MSW and domestic sewage discharge. Solid waste accumulation together with sediment deposit, by nature, may be compared to the sewage sludge generated in WWTPs. The issue of contamination must not be overlooked, as the level of contamination defines the further treatment requirement and applicability of the dredged sediment. Critical in understanding the potential of sediment use is the assessment on how MSW and sewage sludge can be treated. The report, therefore, provides a short insight into the processes of MSW and sewage sludge treatment and parallels them with sediment treatment options.

There is no magic formula that can be universally applied and, adding to the complexity, the diverse nature of water networks further restricts the applicability of approaches. Despite these challenges, the clear understanding of sediment features is the first crucial step to construct sediment management strategies, and the generated amount must be factored in the processes. The estimation of sediment load, however, is not sufficient to formulate such strategies. Sediment generation and deposition in urban and agricultural areas up the ante, as contaminated sediment has complex interactions with water resources, ecosystems, and human population.

FAO (1996) distinguishes two major dimensions of sediment-induced pollution: physical dimension, and chemical dimension:

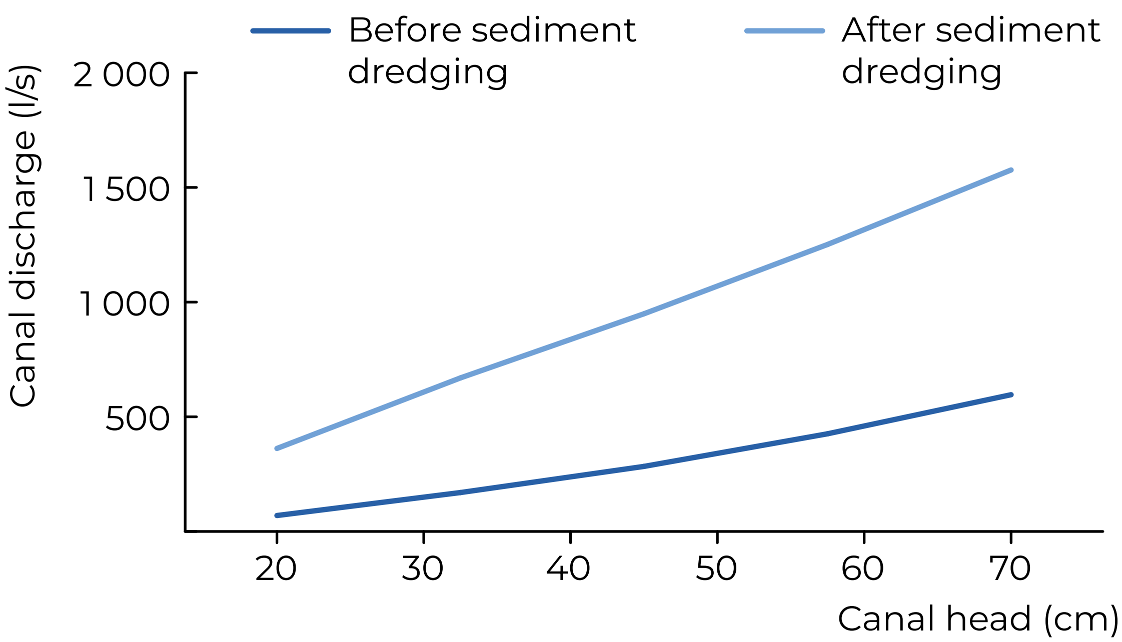
- Physical dimension: topsoil loss and land degradation by gullying and sheet erosion, leading to both excessive levels of turbidity in receiving waters and off-site ecological and physical impacts from deposit.
- Chemical dimension: the silt and clay fraction (particle size <63 μm) is a primary carrier of adsorbed chemicals, which are transported by sediment and may end in the aquatic system.

As per physical pollution, the effect of turbidity is ambiguous. On one hand, turbidity disrupts the penetration of sunlight into the water column, thus affecting the natural habitats of aquatic ecosystems. On the other hand, turbidity can be beneficial in some cases, if the nutrient-rich sediments are mixed with water. The increasing level of turbidity might be more relevant in the case of natural water bodies of aquatic ecosystems. The physical pollution of sediment in engineered infrastructures has other types of consequences that are generally considered detrimental. The accumulation of sediment has a direct implication on the performance of irrigation infrastructure (Samiyev *et al.*, 2020).

Figure 1. A gate and irrigation canal in Akkar, north Lebanon.

El-Bared irrigation system in Akkar is a glaring instance of reduced canal capacity due to the thick sediment deposits. The irrigation system has a high sedimentation rate due to the basin contributions to the deposits in El-Bared dam, the lack of sediment extractor around the canal intakes, the occasional but intense runoff from the surrounding hills, and the lack of sufficiently high canal banks in downstream areas to prevent overflowing. To visualize the direct impact, discharge rating curves are calibrated pre- and post-maintenance of the main irrigation canal and shown in Figure 2. The post-maintenance curve shows that sediment dredging from the irrigation canals considerably increases the velocity and water depth, thus resulting more than twice the water flow rate.

Figure 2. Discharge curve before and after sediment dredging in Akkar canal



Source: author's own elaboration.

The regular sediment removal has further benefits, such as the reduced exposure of the pumps to erosion and of the pipes to clogging, the more efficient use of offtakes, and the more equitable water distribution between upstream and downstream farmers. Another non-negligible impact of the sediment removal is the elimination of the "breeding ground" for pollution. As sediment deposit can trap and settle down the MSW, the canal bottom may involuntarily become a major source of the transport of nonpoint pollution.

The chemical pollution of sediment is often unseen but more hazardous than the physical pollution. Chemical pollution is tied to both particle size and the amount of particulate organic carbon of the sediment. The chemically active fraction of sediment is usually the portion smaller than 63 µm, by which the heavy metals and other chemical parameters can be attracted. Also, toxic organic contaminants are associated with the organic carbon of the sediment, thus being bound, and easily transported or deposited. The chemical pollution of the sediment ultimately determines its applicability for different purposes, such as agriculture. This report, therefore, emphasizes on the chemical dimension of the sediment.

Figure 3. Dredging and canal cleaning in Akkar, north Lebanon

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As contamination of sediment is obvious in El-Bared irrigation system due to the MSW disposal and the uncontrolled sewage discharge, the report takes the most pessimistic scenario and assumes that the accumulated sediment is sewage sludge. Such careful approach should be maintained until the evidence proves beyond a doubt that the sediment contamination does not exceed any pollutant thresholds or the standard quality parameters.

Municipal solid waste and sludge treatment options

A regrettable global trend, MSW, untreated wastewater and sludge have been directly released to the surface water bodies, including seas and oceans due to the lack of infrastructure, legal regulations or enforcing rules (Cieślik *et al.*, 2015; Singh and Agrawal, 2008). This leads to potential environmental, health and social risks. Regarding sewage sludge, the increasingly strict rules and higher standards concerning the quality of treated wastewater before its discharge to natural water bodies increases the produced sludge amount. The management of sewage sludge has become a major environmental and economic concern globally, and adding to its complexity, the economic aspect of sludge management is still in its infancy (Breda *et al.*, 2020; Fuerhacker and Haile, 2010; Fytili and Zabaniotou, 2008; Kelessidis and Stasinakis, 2012; Chen *et al.*, 2012). The conventional practices of disposing MSW and sewage sludge include landfilling, land reclamation, and application to agricultural soils.

Although these methods carry high risks to the human health and the environment if the waste is not properly treated, the contained nutrients can be recycled, and the process can be integrated into sustainable agricultural practices (Frišták *et al.*, 2018; Fytili and Zabaniotou, 2008; Kelessidis and Stasinakis, 2012; Mininni *et al.*, 2015; Zaker *et al.*, 2019; Debiase *et al.*, 2016; D. Romanos, 2020; Seleiman *et al.*, 2020; Kumar *et al.*, 2017). The objective of MSW and sludge

Figure 4. Agricultural landscape in Akkar, north Lebanon

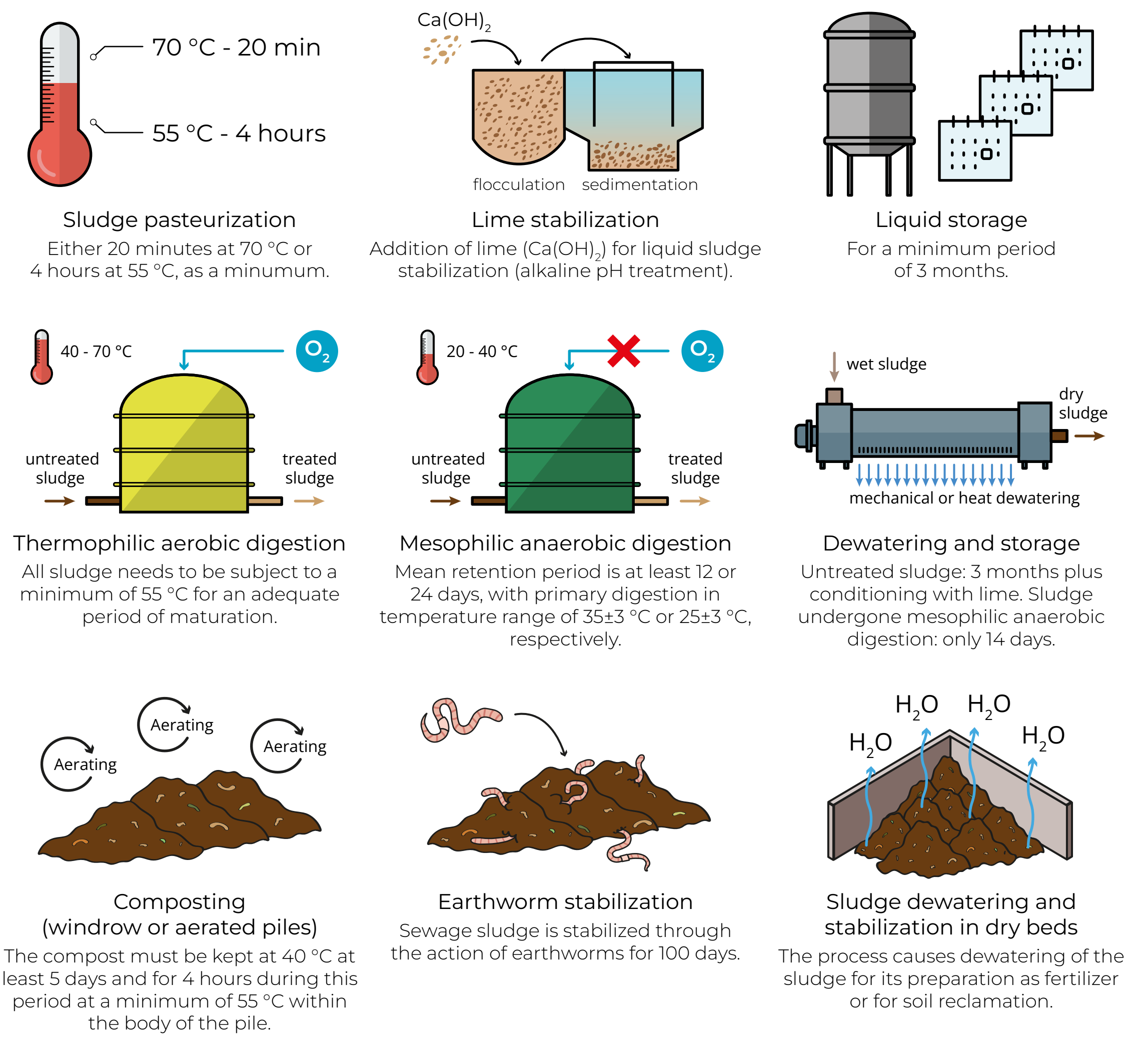
management practices is to reduce the environmental impact and to enhance their recycling potential. Thus, the management of MSW, sewage sludge, as well as the contaminated sediment can be integrated into the circular economy to turn waste into resource.

What makes sewage sludge comparable to contaminated sediment, and what are the practiced treatment steps? According to FAO, the wastewater treatment methods entail a sequence of physical, chemical, and biological processes and operations to take out solids and organic matter from wastewater. The physical treatment starts with a filtering procedure to remove the coarse solids and other large materials. As first step, the flow velocity is reduced to separate and settle the organic and inorganic solids to sediment (FAO, 1992). The next step is the secondary treatment to remove the biodegradable particles and colloidal organic matter via aerobic treatment processes. Thus, aerobic microorganisms play a key role in wastewater treatment. Natural, low-rate systems require a considerable land extension to be implemented, but are considered very effective in removing pathogens (FAO, 1992). In cases where other specific pollutants (i.e. nitrogen or phosphorus) are present in the wastewater, a tertiary or advanced treatment is employed. An example of advanced treatment process is the use of chemicals for disinfection, frequently chlorine, ozone or ultraviolet radiation (FAO, 1992).

Based on the applied treatment process, sludge can be classified as primary, secondary or tertiary sludge. Primary sludge is made up of settled solids separated from the raw wastewater, while secondary sludge contains biological solids as well as additional settable solids. The separation of primary and secondary sludge before its treatment and disposal can optimize the two separate processes (Mininni *et al.*, 2004). The secondary sludge can be used as fertilizer in agriculture due to its high content of nitrogen and phosphorus and its negligible content of pathogens. On the other hand, the primary sludge can be anaerobically digested to produce biogas as sustainable energy source.

There are also successful case studies on co-composting MSW and sewage sludge and mixing dredged sediments with manure and compost to make the recycle process more integrated (Hamzawi *et al.*, 1998; Lu *et al.*, 2009; Oliveira *et al.*, 2017). Finally, microbes such as viruses, heavy metals, phosphorous or nitrogen might remain in the sludge produced in the tertiary treatments (European Commission, 2002). Fytili and Zabaniotou (2008) conducted a comprehensive review of nine treatment processes of sewage sludge, illustrated in Figure 5, which may be considered when management strategies are outlined (Fytili and Zabaniotou, 2008).

Figure 5. Common sludge treatments



Source: author's elaboration based on Cieślik *et al.* , 2015 and Fytili and Zabaniotou, 2008.

Similar to the sludge, if severe contamination of the sediment is suspected, similar treatment procedures should be followed. It depends on the initial laboratory analysis that gives an indication on the levels of contaminants. A major difference between the sludge and the sediment is the location and efforts to collect and transport sediment from irrigation or water networks. While sludge is generated as a by-product of the water treatment and is internalized into the treatment process, sediment load in irrigation systems is dispersed and varies spatially and temporarily as per its dynamics. While this feature adds to the complexity of the quantification process, it can also undermine the financial recovery of the use process.

Figure 6. Dredging and canal cleaning in Akkar, north Lebanon

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Nevertheless, when the cost-benefit ratio of sediment use is calculated, it is important to incorporate the externalities, such as the direct gains of unloaded sediment and the improved infrastructure performance. The moisture of the sediment has a paramount importance when selecting the treatment method. The moisture content of canal sediments may differ from that of sludge, depending on the flow conditions in the canal and the wetness of the sediment during dredging. The low moisture content of the sediment will reduce transportation costs while defines the applicability of the treatment methods. Once the dredging and transportation are settled, the process of sediment reuse corresponds to the treatment options of sludge management. More than that, if the sediment is less or not contaminated, the intricacies of process and costs of treatment decrease exponentially.

Alternative options of sediment use

Landfilling and land reclamation have been the most popular disposal methods of MSW, sludge and sediments due to their relatively low investment requirement. However, such disposal poses severe environmental and health risks and increases the operation cost due to the high transportation cost. As available land for landfilling is becoming scarce, and environmental standards are more increasingly stringent, these methods are more withdrawn lately (Chen *et al.*, 2012; Cieślik *et al.*, 2015; Soria-Verdugo *et al.*, 2017).

Furthermore, considering the target environment of the highly populated coastal Lebanon, this approach is neither feasible nor recommended. Incineration is widely used but given its considerable emission and discharge of heavy metals, the method cannot be considered in line with the sustainability objectives (Fytili and Zabaniotou, 2008).

Beyond landfilling or incineration, thermal processes like combustion, wet oxidation, gasification, and pyrolysis alternative methods are available to exploit the energy potential and prevent the already mentioned health and environmental risks (Aziz *et al.*, 2013; Kelessidis and Stasinakis, 2012; Rulkens, 2008; Sözen *et al.*, 2019; Zhang *et al.*, 2017). Sludge is considered to have a similar calorific value as brown coal, yet the main challenge is the high water content of wet sludge (Fytili and Zabaniotou, 2008). Pyrolysis is considered to be the most promising technique for energy production. Pyrolysis is a thermal treatment using anoxic atmosphere and high temperature. By-products generated in the reactions are biofuels, biogas and biochar. The amount and quality of these by-products, and hence the efficiency of the treatment, depend on the characteristics of the substrate (MSW, sediment or sludge), the heating rate and the temperature. Providing a fresh perspective, Frišták *et al.* (2018) investigated the potential use of sewage sludge pyrolysis to produce a safe source of phosphorus for agriculture. With many variables at stake, the research findings are in disarray, and a large number of further experiments are rolled out, mainly with sludge, to reduce the energy requirements and improve the quality of the products obtained after pyrolysis (Zaker *et al.*, 2019).

Figure 7. Urban landscape around the irrigation canal in Akkar, north Lebanon

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According to the review of Zaker *et al.* (2019), the results reported in the ample number of publications are ambiguous, as they depend on the characteristics of the sludge, the type of reactors, and other case-specific features. Authors, therefore, suggest that further research about catalytic pyrolysis should be conducted, as these catalysts seem to improve the quality of biofuel and reduce the temperature needed for the pyrolysis process, thus increasing the energy efficiency.

Research gaps remain, including optimal feed ratio to the sewage sludge, the kinetics of the catalytic conversion, or the co-pyrolysis of sewage sludge with other carbon-based materials such as plastics. In line with the production of syngas from sludge, Kokalj *et al.* (2017) described two possible gasification processes of wet sludge, including the syngas similar to water gas to be used by natural gas engines or syngas similar to wood gas. Dentel *et al.* (2004) reported on the direct generation of electricity from sewage sludge in laboratory conditions by using graphite electrodes in the same way as energy is harvested from marine sediments. Jiang *et al.* (2009) also demonstrated that electricity can be generated directly from sludge by means of a microbial fuel cell.

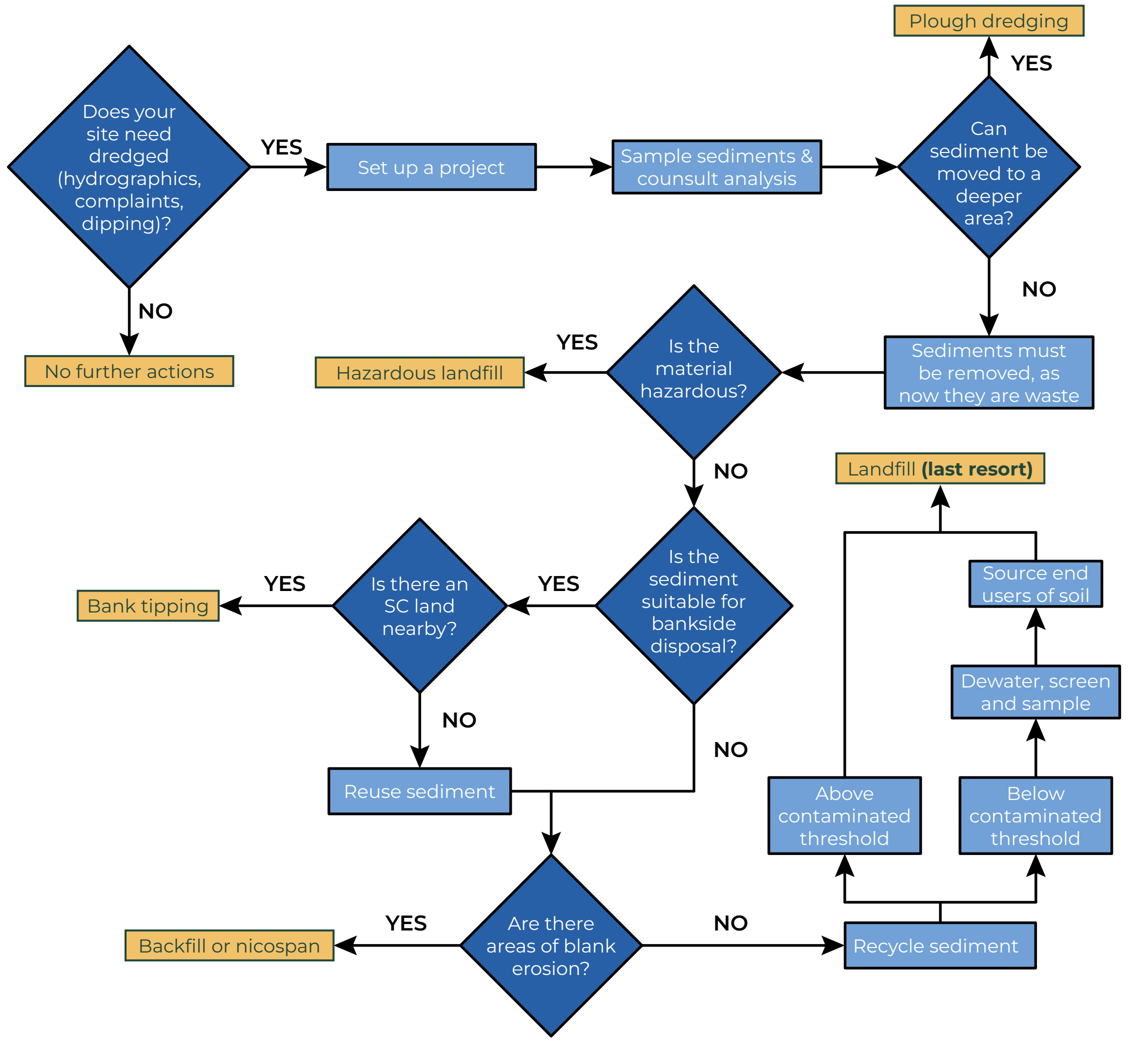
Zhang *et al.* (2012) conducted further research to obtain more electrical power from sludge by using a biocathode into a three-chamber microbial cell. The methods of using sludge for energy source are evolving rapidly. Undoubtably, such methods pave the way for improved, circular economy that minimizes the waste and the risks associated with treatment methods. However, there are several limitations that hamper their application, among other, the return on investment, the required economies of scale, the available infrastructure, the treatment of by-products, and the input efficiency.

Overly sophisticated technologies are not appealing when the enabling environment is not favourable, and the surrounding conditions are fragile. Furthermore, all these technologies must be scaled up to economically viable options beyond their scientific interest. In support of the efforts to make production cycles more integrated, the application of sediment as a nutrient source is increasingly in the forefront. Highlighting the fact that each method has its advantages and disadvantages, Hospido *et al.* (2005) suggested that the application of digested sludge to agricultural land is a promising alternative, even compared to the thermal processes.

Several country and regional experiences prove the feasibility of sludge use for agricultural purposes. For example, following a long traditional practice, Chen *et al.* (2012) concluded that the application to lands after anaerobic digestion and composting can be the most suitable disposal method in China. Sludge treatment and composting for agricultural purposes are already considered as the primary disposal method in many European countries, such as Ireland (Collivignarelli *et al.*, 2015; Mininni *et al.*, 2015). Ingallinella *et al.* (2002) proposed a treatment method of faecal sludge coming from high-density urban areas through a semi-centralized system, where sludge is dewatered and made available for disposal in agricultural areas.

Sediment use from peri-urban irrigation schemes should be viewed in parallel with the sewage reuse processes. Lord (2017) proposed a decision-support tree for the classification of sediment use in the context of circular economy (Figure 8).

Figure 8. Proposed scheme for the reuse of dredged sediments



Source: reproduced from Lord, 2017.

Other works address the use of sludge as a component for construction materials, as an ingredient of cement or mortar (Ahmad *et al.*, 2016; Ahmad *et al.*, 2017; Alqam *et al.*, 2011; Fytili and Zabaniotou, 2008) or vitrification (Cieślik *et al.*, 2015).

Sediments are also recommended to be used to manufacture bricks, ceramics and concrete (Sigua, 2009). Finally, dredged materials are often used for the restoration of beaches and littorals (Sigua, 2009). While the process generates only indirect economic benefits, its environmental contribution is significant. Table 1 shows a synthesis of disposal methods for sludge, sediments and MSW.

Table 1. Synthesis of disposal methods for sludge, sediments and municipal solid waste

Method	Advantages	Limitations	Reference(s)
Land filling Land reclamation	• No investments	• High environmental and health risks • Transportation costs • Increasing land scarcity for this purpose	Cao *et al.*, (2011) Kelessidis and Stasinakis (2012)
Agricultural use Soil amendment	• Reuse of nutrients • Reduction of chemical fertilizer use • Positive effects on soil	• Environmental and health risks • Social acceptance	Breda *et al.* (2020) Hospido *et al.* (2005) Hossain *et al.* (2017) Maryland Department of Environment (2017)
Incineration Combustion	• Energy production	• Discharge of combustion gases	Barber (2009)
Pyrolysis	• Bio-oil, biogas and bio-char production • No combustion gases	• Investment costs • Operation costs	Sözen *et al.* (2019) Zaker *et al.* (2019)
Construction	• Cost reduction	• Possible environmental risks	Ahmad *et al.*, (2017) Cieślik *et al.* (2015) Sigua (2009)
Beach and littorals nourishment	• Positive environmental impact	• Limited space	Sigua (2009) Maryland Department of Environment (2017)

Treatment process in the context of Lebanon

The public services reach the limit of their capacity in Lebanon, and the on-going, multifaceted crises further disrupt the delivery services. This is particularly acute in sectors that fail to recover their costs. Waste management and sewage treatment are amongst the most affected services, and the mounting issue of uncollected trash and the raw sewage discharge into natural water bodies have far-reaching consequences (Romboli *et al.*, 2018). Less than 60 percent of the households are connected to wastewater utilities, and the large regional disparities have persistent effects on the living standards. Most of the wastewater is discharged into surface water and the Mediterranean without any treatment (UN-ESCWA, 2017).

Figure 9. Canal outlet at the sea in Akkar, north Lebanon

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The MSW sector shows a similar picture, and the compounded crises further exacerbated the difficult situation by the sudden tightening of financial resources. The emergency measures taken by Government to solve the problem of the MSW accumulation led to the overloading of old landfills and the opening of new sites. However, this solution is neither supported nor sustainable, and there is an urgent need for long-term strategies (Salloum, 2020; Romboli *et al.*, 2018). According to the Country Environmental Analysis published by the World Bank in 2011, the production of dry sludge in Lebanon could reach 306 tonnes/day a decade ago.

Currently, this potential is far from being exploited, as the sludge is mostly disposed in sanitary landfills. Nonetheless, there is an increasing interest in employing treated or digested sludge as fertilizer or as soil amendment and conditioner, trying to add value to this potential resource. Incineration is also being considered as a suitable sludge treatment process due to its ability to reduce its weight by tenfold and to eliminate bacteria, pathogens and viruses (World Bank, 2011).

Box 2. Guidelines for wastewater reuse in Lebanon by FAO

FAO introduced a pilot programme to assist the Government of Lebanon in the development of national guidelines for wastewater reuse (FAO, 2011). While improving the practices of wastewater reuse was the main objective of the pilot, the assessment touched upon the use of sludge. Sludge can be considered as an important by-product of water reuse practices, therefore, the overview of the recommended treatment methods can highlight the entry-points, where the potential of treatment cycle can be further developed. The proposed treatment options were defined along a crop classification.

The guideline concluded that water reuse is a significant source of water for agriculture, but the potential is underexploited. More concerted efforts are required to better utilize the water resources, including the sludge.

Parameter	Class I	Class II	Class III
Restrictions	Produce eaten or cooked; irrigation of greens with public access	Fruit trees, irrigation of greens and with limited public access; impoundments with no public water contact	Cereals, oil plants, fibre and seed crops, canned crops, industrial crops, fruit trees (no sprinkler irrigation), nurseries, greens and wooden areas without public access
Proposed treatment	Secondary, filtration and disinfection	Secondary, storage or maturation ponds or infiltration percolation	Secondary and storage/oxidation ponds
Biological Oxygen Demand (mg/l)	25	100	100
Chemical Oxygen Demand (mg/l)	125	250	250
Total Suspended Solids (mg/l)	60 (200 WSP)	200	200
pH	6-9	6-9	6-9
Residual chlorine (mg/l)	0.5-2	0.5	0.5
Nitrate-nitrogen (mg/l)	30	30	30
Faecal coliforms (in 100 ml)	<200	<1 000	None required
Helminth eggs (in 1 l)	<1	<1	<1

Figure 10. Farmer's group in Akkar, north Lebanon

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In Lebanon, the transportation of sludge is a limiting factor that ultimately determines its wide-spread use. In inland WWTPs, where agricultural lands are nearby, sludge should be treated for agricultural use as land conditioner or fertilizer. Karam *et al.* (2013) suggested that stabilized sludge should be given to the farmers as an incentive to promote its use (Karam *et al.* 2013). Incineration is only recommended in special cases, such as hospital and industrial liquid wastes (World Bank, 2011).

However, large-size WWTPs located in coastal areas, by default, are the main sludge producers. As the coastline hosts only two agriculturally significant areas in the southernmost and northernmost parts of the country, a technical alternative for sludge management in the coastal area can be its anaerobic digestion. In turn, the produced power can be used to sustain the WWTP energy requirements (World Bank, 2011). Only a few experiments are available on the re-use of sludge and sediment, which are discussed in the coming sections.

SECTION 3

THE POTENTIAL APPLICATION AND LIMITATIONS OF DREDGED SEDIMENTS IN AGRICULTURE

Sludge and sediment application, either row or treated, to improve soil fertility is a common practice worldwide. However, the rule of "no-one-size-fits-all" applies even here, and advantages and disadvantages must be taken into account (Hospido *et al.*, 2005). Building on the assumption of similarity between contaminated sediment in irrigation canals and sludge, this section builds around the assessment of potential and limitation of the sediment use in agriculture.

On one hand, sewage sludge can potentially improve soil characteristics and supply nutrients such as nitrogen and phosphorus and micronutrients. On the other hand, it may also contain excessive concentrations of contaminants such as heavy metals (like copper, cadmium, zinc, nickel, lead, mercury, etc.), organic pollutants and pathogenic microorganisms. Additional constrains on the safe use of sludge and dredged sediments are created by the seasonal variability in composition and characteristics (Singh *et al.*, 2011; Singh and Agrawal, 2008). The cumulative effect of application on lands also depends on the frequency and duration of the application.

The global experiences of positive effects on crops and soil

Several experiments show positive effects of sludge application on crop production. For example, Epstein *et al.* (1976) measured the effect of different rates of anaerobically digested sludge (from 0 to 240 tonnes/ha) and dry sludge compost, using two pH levels, on maize. The conclusions suggest that both sludge and compost increased the water content and water retention capacity of a silt loam soil.

Wang (1997) reported the benefits of sewage sludge in comparison to the use of chemical fertilizers or manure, as it increased soil organic matter, phosphorus and nitrogen content. Significant yield increases were also reported in the cases of tomato (11 percent), wheat (54.1 percent) and Chinese cabbage (120 percent). According to the author, the combination of composted sludge and chemical fertilizers proved promising. Reporting on another successful case, fertilization with digested sludge over four years resulted in an increase of cotton yield in Greece (Samaras *et al.*, 2008). The application of raw, lime-stabilized or composted sludge enhanced biomass production of rapeseed, wheat and maize (Du *et al.*, 2012). Özyazici (2013) also concluded the positive effect of digested sludge on crop production in a wheat-cabbage-tomato rotation. The recommended rate based on the study experiment was high though, amounting 20 tonnes/ha of dry digested sludge.

Biomass and yield increase, as well as better grain quality, were reported in wheat field in Egypt, where lands were fertilized with sludge in a two-season experiment. The increase was achieved even though a low rate of 10 tonnes/ha was applied during the experiment. The pre- and post-assessment showed no critical level of heavy metals neither in the sludge nor in the grains and roots (Mansour *et al.*, 2013; Mazen *et al.*, 2010).

Singh and Agrawal (2008) compiled the results and conclusions of numerous studies in their review titled "Potential benefits and risks of land application of sewage sludge". They highlighted the importance of the interaction of soil-sludge characteristics, including the bioavailability of toxic compounds. For example, the pH of the sludge-soil mix has a key role in the applicability. In conclusion, sludge applications to crop fields proved to increase soil aggregate stability, water-holding capacity, porosity, and humus content while reducing its bulk density and erodibility. Entailing equivocal findings, sludge can either increase or decrease soil pH, depending on the acidity or alkalinity. After a 16-year experiment in a calcareous soil in Spain, Roig *et al.* (2012) observed that soil properties improve with sludge application rate up to 40 tonnes/ha, without increasing soil salinity (Roig *et al.*, 2012). However, ion toxicity in onion occurred due to cadmium accumulation.

Figure 11. Crop field in Akkar, north Lebanon

Darmody and Ruiz-Diaz (2017) observed significant positive effects of dredged sediments on maize yield in a sandy soil, as well as improved soil texture and fertility (Darmody and Ruiz-Diaz 2017). The positive effects of sediments (from rivers and lakes) on soil properties have been also investigated globally (Darmody and Ruiz-Diaz, 2017; Lord, 2017; Sigua, 2009; Sigua *et al.*, 2004). The application of lake-dredged sediments to pasture lands in Florida (United States of America) was documented by Sigua (2009).

Global experiences include studies on eliminating the risk of pathogens in sludge to ensure safe application (Usman *et al.*, 2012). These studies show that reused and treated sludge and sediment have multiple advantages, such as the economic disposal, the reduction of chemical fertilizers, and the improvement of soil properties. According to the global review of Usman *et al.* (2012), heavy metal levels in most of the sludge samples in the European Union, India and Pakistan were under the critical levels when assessed against the nationally defined standards of US, Japan and Germany. Smith (2009) found that metals are usually bound to the organic matrix of the compost of MSW or sludge, which reduces the bioavailability for crops.

Similar studies were conducted also in Lebanon to understand the feasibility of sludge application, based on the FAO guidelines (FAO, 2010). An experiment in wheat fields in the Bekaa Valley showed that sludge application improved soil characteristics and increased wheat grain protein and fibre, while heavy metal contents in both soil and crops remained below the thresholds. However, the impacts must be monitored over a longer period to conclude far-reaching recommendations (Romanos, 2020; Romanos, 2021).

Identified risks and limitations

The potential side effect of sludge application on soil salinity and increased chloride levels must be carefully accounted (Du *et al.*, 2012; Epstein *et al.*, 1976; Samaras *et al.*, 2008). Concerning the sanitary risks, Pescod (1992) alerted about the hazardous components of sewage sludge and its environmental risks. Gaspard *et al.* (1995) emphasized the elevated risk of urban sludge application to land due to the high resistance of nematode eggs to treatment processes. Similar risk factors are also highlighted regarding the management of faecal sludge in urban areas of emerging countries (Ingallinella *et al.*, 2002). To lower the risk of raw sludge use in China, studies highlight the importance of affordable technologies such as composting for stabilization and preparation (Wang, 1997). Epstein *et al.* (1976) reported that both positive and negative effects of heavy metal are lower when the sludge is composted.

Sludge stabilization treatment determined the solubility of heavy metals, as the concentrations of chromium, mercury and nickel were here in anaerobically stabilized sludge than in aerobically and non-biologically treated sludge in Croatia (Černe *et al.*, 2019). Nevertheless, eight out of nine sludge samples were considered applicable without notable risks in the short term. Another potential risk is that compounds like grease, heavy metals, phenolics and polycyclic aromatic hydrocarbons can adversely affect soil microbiota, reducing soil fertility (Cieślik *et al.*, 2015). Consequently, a physicochemical analysis of sewage sludge is recommended as a prerequisite before application.

Kidd *et al.* (2007) suggested that the risk of leaching of phosphorus and some metals like copper and zinc after repeated land application of digested sludge is greater than risk of heavy metals entering the harvestable product. Even though the heavy metal content of the soil increased, heavy metals were not taken by the crops. Evaluating the effects on native grasses in China, Wang *et al.* (2008) conducted an experiment consisting of six rates of sludge land application from 15 to 120 tonnes of dry sludge per hectare.

Figure 12. Equipment in the water quality laboratory of Akkar, north Lebanon

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Although they confirmed the benefits of sludge on soil characteristics, sludge application was recommended rather to forests and grasslands, as cadmium concentration exceeded the acceptable threshold after 16 months application. The uptake of some heavy metals by plants and their presence in their edible parts is a severe constraint. Some of the evaluated cases highlighted the accumulation of cadmium by lettuce and spinach, the accumulation of lead by kale and copper, zinc and nickel by sugar beet (Singh and Agrawal, 2008). Therefore, the use of sludge and contaminated sediment should be evaluated per crop classification, with special emphasis on leafy vegetables and fresh produces.

Sludge application in agriculture can also change the microbial and enzymatic activity of soils due to the higher availability of toxic compounds. Also, the presence of pathogenic bacteria is certainly amongst the greatest concerns. Studies investigating the raw sludge use suggested further experiments to understand the interactions in different soil types and the effects on the microbiology, surface and groundwater, eventually on the human health (Singh and Agrawal, 2008).

Figure 13. Water quality laboratory at the North Lebanon Water Establishment

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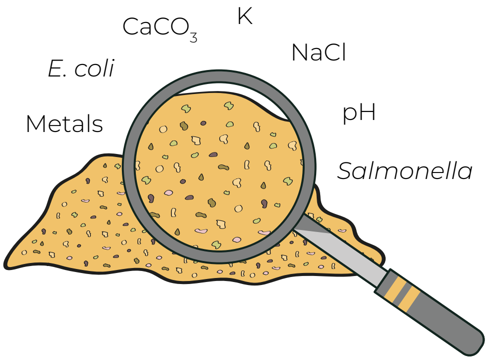
Evaluating the potential toxicity, Bright and Healey (2003) measured the content of various organic contaminants in 36 samples of fresh sludge from five large WWTPs in Canada, as prior legal limitations focused on heavy metals. They concluded that the regulations seem sufficient for preventing the environmental damage from organic contaminants when sludge is applied to uncontaminated soil. The analysed organic compounds comprised dioxins and furans, phthalate esters, or volatile organics.

However, the same did not apply to petroleum hydrocarbon constituents or their microbial metabolites, which would require special attention, together with other organics if sludge application is repeated. Healey and Fenton (2017) found microplastics in several sludge samples from Irish WWTPs, which can accumulate in the soil and finally enter the food chain. Moreover, pharmaceuticals and other drugs are currently seen as a new threat for the application of sludge to soil (Díaz-Cruz *et al.*, 2009; Fijalkowski *et al.*, 2017; Ivanová *et al.*, 2018). Müller *et al.* (2000) reported the notable occurrence of herbicides and pesticides in sediments from irrigation canals in sugarcane and cotton areas in Queensland, Australia (Müller *et al.*, 2000).

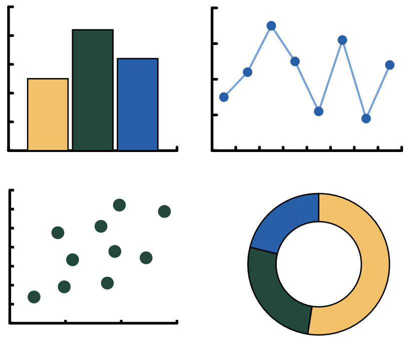
In Lebanon, Romanos *et al.* (2019) evaluated the levels of heavy metals, pathogenic microorganisms and phytotoxicity of sludge coming from three different WWTPs in the Bekaa Valley (Romanos *et al.*, 2019). From the three WWTPs, two relied on solar thermal treatment combined with liming to stabilize the sludge, while the third used a special digester. Only one case proved the presence of heavy metals, having the zinc concentration higher than the acceptable national standard. What makes sludge use concerning in Lebanon is the parasitological risks due to the presence of *Escherichia coli*, *Staphylococcus aureus* and Acinetobacter. Therefore, composting, or other treatment method is a prerequisite to recommend sludge for agricultural use.

Key recommendations

Previous characterization of the sediments (nutrients, pollution, pathogens, etc.) and its sources is necessary to avoid risks.



Regular soil analysis and monitoring (physical, chemical and biological properties) are required during the application.



Applicability of contaminated sediement use must be evaluated per crop classes.

Optimal frecuency of sediment use can lower the cost and required resources for analysis and monitoring.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SECTION 4

REGULATION FRAMEWORK FOR THE USE OF SLUDGE IN FARMING SYSTEMS

International standards

The compliance with environmental regulations that advise on the safe disposal of sediments and biosolids are necessary to mitigate the risks. As the global interest in improving the integrated cycle of natural resource management is growing, an increasing number of countries embark on the development of sediment quality guidelines. Although the first-generation guidelines focus mostly on heavy metals, the recent publications also involve the risk assessment of biological contamination.

The major shortcomings of the existing guidelines are the compound-specific approach and the lack of the integration of the ecosystem (Burton, 2002). However, some comprehensive guidelines exist, which can provide a baseline for further evaluations, for example the Regulatory Applications Of Sediment Criteria by the United States Environmental Protection Agency (USEPA) in 1987 and the Dredge Material Management Program in Maryland, Australia (USEPA, 1988; Maryland Department of Environment, 2017).

According to the European Union Waste Framework Directive, sediments from canals should be considered as waste and must be treated according to country-specific waste regulations (European Commission, 2008). The European Union Directive is based on a "waste hierarchy" (Figure 14) and establishes that waste needs to be managed:

- without endangering human health and harming the environment;
- without risk to water, air, soil, plants or animals;
- without causing a nuisance through noise or odours;
- without adversely affecting the countryside or places of special interest.

However, Renella (2021) reported that recycled sediments are not widely used in European Union agriculture due to a lack of clear regulations (Renella, 2021). The origin, nature and potential disposal options of sewage sludge are ruled by many direct and indirect regulations. If sewage sludge is marketed as organic amendment, the compost produced from sewage sludge is subject to fertilizers regulations (Soler-Rovira *et al.*, 1996). In Japan, when employed in agricultural use, sludge compost must fulfil the "Fertilizer Control Law" that includes restrictions on pollutants (Leschber, 2002).

Figure 14. Five-step waste hierarchy of the European Union

Source: reproduced from EC, 2008.

In the European Union, sewage sludge is mentioned in several Directives such as the one on water (2000/60/EC), urban wastewater treatment (91/271/EEC), landfill (99/31/EC), incineration (2000/76/EC), and other relevant sectors (Inglezakis *et al.*, 2011; Spinosa, 2001). The single legislative act proposed at the European level is the Council Directive 86/278/EEC of 12 June 1986, which came in force to address the use of sewage sludge in agriculture (Soler-Rovira *et al.*, 1996). It defines that any sludge shall be treated before being used in agriculture and exclusively under certain conditions. Untreated sludge can be accepted if it is injected or worked into the soil (EEC, 1986). However, member States of the European Union must implement monitoring systems to ensure up-to-date records of the quantities of the produced sludge and the quantities supplied for use in agriculture, composition and properties of the sludge, the type of treatment carried out, the names and addresses of the recipients of the sludge, and the place where the sludge is to be used.

Likewise, the countries shall follow the reference methods for sampling and analysis of sewage sludge and farms soil described in Appendix II C of the Directive 86/278/EEC of 12 June 1986 (Soler-Rovira *et al.*, 1996). The European Union Directive sets the limits of heavy metals (cadmium, copper, mercury, nickel, lead and zinc) in the sludge, the soil where applied, and the maximum annual loads of heavy metals to be put into the soil. If the pH of the soil is consistently lower than 6, these limits should be reduced as the mobility of heavy metals intensifies (Soler-Rovira *et al.*, 1996).

Inglezakis *et al.* (2011) reported that those limits, based on precautionary calculations, are higher than those in the United States of America, but lower than the limits that many European countries impose nationally, for example Denmark, Finland, Sweden, Netherlands, Austria, Belgium, France and Germany (Inglezakis *et al.* 2011, Leschber, 2002). Several European Union Member States established stricter regulations, including limits on the concentration of additional heavy metals (chromium, arsenic, molybdenum, cobalt and selenium), synthetic organic compounds and pathogens (Mininni *et al.*, 2015). The Working Document on Sludge of the European Commission (EC, 2000) defines the limits on heavy metals of the Directive and proposed limit values for organic micropollutants (polycyclic aromatic hydrocarbons, alkyl benzene sulfonates, di(2-ethylhexyl)phthalate, nonylphenol ethoxylates, adsorbable organic halogens, polychlorinated biphenyls and polychlorinated dibenzo-p-dioxins and furans) and pathogens:

- Some European countries adopted limits on absorbable organic halogen, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls, while in the United States of America thresholds for coplanar polychlorinated biphenyls and polychlorinated dibenzo-p-dioxins and furans are imposed (Collivignarelli *et al.*, 2019, Leschber, 2002).
- According to the Working Document, sewage sludge must be tested for *Salmonella* and *Escherichia coli* (EC, 2000). References to other indicators (Enterococci, thermotolerant coliform bacteria, Clostridium perfringens, and helminth eggs) are also included in the national legislation of 11 Member States (Collivignarelli *et al.*, 2019).

The strict regulations for the compositions are gradually relaxed along the treatment process. In South Africa, for example, limits vary according to the four classes systems: sludge and faecal matter (class A), sludge after mesophilic anaerobic digestion (B), and sludge after hygienization like composting, lime treatment and radiation (C and D). The Working Document on Sludge lays down the conditions that allow the application of sewage sludge to animal feed crops, horticultural and fruit crops without withholding periods – only those streams that undergo advanced treatments or “hygienization”, as opposed to conventional treatments (listed in Annex I of the Working Document, EC, 2000).

Attention should be paid to the nutrient balances in soils. In the United States of America, nutrients are carefully assessed in sensitive watersheds. Also in Australia, the maximum permissible load of applied dry matter is reduced when nutrients are sufficiently available (Leschber, 2002). In the frame of a Multilateral Environmental Agreement, the Mediterranean countries forbid direct dumping of sludge and sewage water into the Mediterranean Sea, as part of the Mediterranean Action Plan, proposed in the Barcelona Convention in 1976 (UNEP, 1977).

Figure 15. Seaside in Akkar, north Lebanon

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Regulatory framework in Lebanon

Environmental issues in Lebanon are under the authority of the Ministry of Environment, which implements its policies via the Council for Development and Reconstruction. The government of Lebanon launched a program on environmental regulations in the 1990s, based on which the Ministry of Environment elaborated the State of the Environment Report and a Strategy Framework in 1996.

The second State of the Environment Report came into force in 2002 and was updated in 2011, together with a draft National Environmental Action Plan in 2006. The latter contains the seven objectives defining the environmental strategy of the Ministry. In addition, Lebanon recently developed several sectoral strategies, programs, and action plans which can be associated with the management of sludge, in line with its global commitments:

- National Biodiversity Strategy and Action Plan (1998);
- Work Plan for the Treatment of Hazardous Wastes in Lebanon (2001-2002);
- National Implementation Plan for the management of Persistent Organic Pollutants (2003-2005);
- National Action Plan for Protected Areas (2004-2005);
- National Plan for Quarries Rehabilitation (2005-2008);
- Law no. 690/2005 and Environmental Law no. 444/2002, setting the legal basis for Decree 8633 on Environmental Impact Assessment (2012).

Figure 16. Contaminated environment in Akkar, north Lebanon

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According to the FAOLEX, the Decree 8633 consisting of 17 articles divided into three Chapters aims at being a tool for predicting and mitigating adverse impacts in projects, describing the various measures that need to be considered in the preliminary environmental evaluation of any project. The Decree sets a protocol from screening, scoping, preparation of the environmental assessment, and supervision of the environmental assessment process including consultation and disclosure, up to the rules of monitoring plans (FAOLEX, 2012).

Contaminated sediment of irrigation canals has similar advantages and disadvantages to the sludge application; therefore, it falls under the same regulatory framework. To enhance the regulatory background, the collaboration of FAO and the Ministry of Environment yielded into constructive conclusions that can be taken forward to operationalize the integrated use of sediment. Based on the collaboration, FAO defines full nutrients recovery, application as cheap fertilizer and low disposal cost as benefits, while the presence of pathogens, heavy metals and organic pollutants as potential threats.

Regarding the trace elements, four classes for sludge and sediment use are defined in Lebanon: class A – unrestricted use, class B and C – restricted use, and class D – not suitable for use. In Table 2, the limits of trace element concentration in sludge are shown. When compared to the international guidelines, the agreed ranges of trace elements as per the country regulations are below the European Union levels, but similar to other countries in the region.

Table 2. Limits of trace element concentration in sludge

Area	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Zinc
European Union	20-40	1 000-1 750	1 000-1 750	15-25	300-400	750-1 200	2 500-4 000
France	20-40	1 000-2 000	1 000-2 000	10-20	200-400	800-1 600	3 000-6 000
Germany	5-10	900	800	8	200	900	200-2 500
Belgium (Wallon)	10-20	500	600-1000	10-16	100-300	500-750	200-2 500
Belgium (Flemish)	12	500	750	10	100	600	2 500
Denmark	0.8-200	100	1 000	0.8-200	30-2 500	60-120	4 000
Spain (soil pH <7)	20	1 000	1 000	16	300	750	2 500
Spain (soil pH >7)	40	1 500	1 750	25	400	1 200	4 000
Greece	20-40	-	1 000-1 750	16-25	300-400	750-1 200	2 500-4 000
Ireland	20	-	1 000	16	300	750	2 500
Italy	20	-	1 000	10	300	750	2 500
Luxembourg	20-40	1 000-1 750	1 000-1 750	16-25	300-400	750-1 200	2 500-4 000
The Netherlands	1.25	75	75	0.75	30	100	300
Switzerland	5	500	600	5	80	500	2 000
Syrian Arab Republic (Class A-E)	3-32	100-600	100-1 500	1-19	60-300	150-400	200-2 800
Lebanon (Class A)	5	250	375	4	125	150	700
Lebanon (Class B)	20	500	1 500	15	270	300	2 500
Lebanon (Class C)	32	600	1 500	19	300	400	2 800

* All values are expressed in mg/kg.

Source: FAO, 2010, elaborated from International Guidelines.

The classification of sludge, thus contaminated sediment use also defines the target location:

- Class A – unrestricted use: Public activities site, parks and green areas, agriculture (fresh vegetables excluded), forest, reclamation land, landfills, surface soils within the premises of treatment plants;
- Class B – restricted use: Agriculture (fresh vegetables excluded), forest, reclamation land, landfills, surface soils within the premises of the treatment plants;
- Class C – restricted use: Forest, reclamation land, landfills, surface soils within the premises of treatment plants;
- Class D – not suitable for use: Landfills and surface soils within the premises of treatment plants.

The recommendations on sludge application also extend to the pathogenic organism contents. The ranges of acceptable organism content are more homogenous across the regions than the ranges set for traceable elements (Table 3).

Table 3. Limits of pathogenic organism contents in sewage sludge

Area	Faecal coliforms	*Salmonella*	Helminth eggs
United States of America – Class A	<1 000 MPN/g dry solids	<3 MPN/4 g of dry solids	<1 viable/4 g of dry solids
United States of America – Class B	$<2 \cdot 10^6$ MPN/g dry solids	-	-
Tunisia	$<2 \cdot 10^6$ MPN/g dry solids	-	-
Syrian Arab Republic	<1 000 MPN/g dry solids	<3 MPN/4 g of dry solids	<1/100 ml at 5% dry solids
Jordan	<1 000 MPN/g dry solids	<3 MPN/4 g of dry solids	<1 viable /5 g of dry solids
Lebanon	<1 000 MPN/g dry solids	<3 MPN/4 g of dry solids	<1 viable /5 g of dry solids

Source: FAO, 2010, elaborated from International Guidelines.

For agricultural purposes, the monitoring of the following parameters is recommended: pH of the water, dry matter, organic matters, total nitrogen, ammonium, phosphorus pentoxide, potassium oxide and maximum oxide. The recommended frequency of sludge analysis ranges from 1 to 12 times per year, depending on the theoretical capacity of the WWTP. In terms of produced quantity, the sediment deposit in El-Bared irrigation system does not exceed the capacity of a WWTP below 5 000 population equivalent, thus making the yearly analysis sufficient. The analysis frequency also depends on the dredging schedule, whether it is regular or occasional.

According to FAO (2011), sludge or contaminated sediment use for agricultural purposes in Lebanon must overcome several limitations:

- Biosolid products should not be used for fresh produces, and even for other crops, at least 8 months period should be observed before its application.
- Pasturing should not be practiced within two months after biosolid application.
- Biosolids disposal should be in reasonable distance from water sources, including drains and irrigation systems. The buffer zone between surface water and disposal areas should exceed 750 m and should not cover areas where the depth of wells is less than 150 m.
- The disposal zone should not be steep, and the maximum allowed slope should be less than 5 percent.
- After disposal, 30 days period should be observed before access by people without sufficient protecting clothes and measures.

Figure 17. Agriculture landscape in Akkar, north Lebanon

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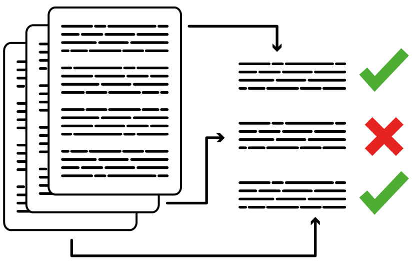
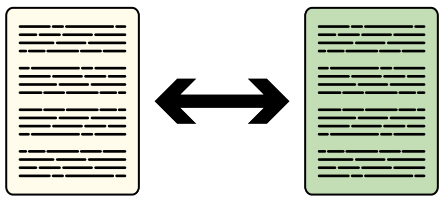
It is important to note that the abovementioned protocol by FAO has been introduced as indicative guidelines in Lebanon; however, it has not been officially adopted and released by the Ministry of Environment. Further experiment is required to set up stringent safeguards for risk mitigation.

Key messages

Specific national regulations for the use of sediments in Lebanese agriculture should be reviewed, endorsed and adopted, including environmental and social safeguards.



The international and national regulations for sewage sludge could be used as a baseline.



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SECTION 5

COMMON PROTOCOLS FOR ANALYSIS OF SLUDGE OR MUNICIPAL SOLID WASTE CHARACTERISTICS

As already discussed, sludge should be analysed before deciding about its final disposal to prevent any risks and make profitable use of it. Therefore, the most common protocols for the analysis of sludge characteristics are compiled in this section.

A detailed characterization of sludge should contain the following information:

- Soil fertility related information:
    - content of macronutrients and micronutrients for crops (namely natrium, phosphorus, potassium, iron, magnesium, etc.);
    - organic matter content, pH, electrical conductivity.
- Toxicity risk related information:
    - content of heavy metals and other inorganic trace elements which could pose any danger;
    - content of organic contaminants (pharmaceuticals, drugs, personal care products, etc.);
    - presence of pathogens (*Salmonella* spp., *E. coli*, *Staphylococcus aureus*, helminth eggs and viruses).

Regarding the first group, it should be noted that the same type of analysis can be conducted on any soil sample, making the use of standard protocols universally applicable. Heavy metal contamination should be measured by spectrometric techniques.

Concerning the characterization of pathogens, metaproteomics could be an alternative tool to get a more in-depth understanding of the microbiological processes in the sludge (Kuhn *et al.*, 2011). Phylogenetic ribonucleic acid analysis is also used to identify the bacteria in the sludge (Snaidr *et al.*, 1997). The International Organization for Standardization (ISO) provides reference to these protocols (Table 4).

Cieślik *et al.* (2015) presented an exhaustive review of the analytical methods that are applicable to each type of sludge according to its treatment and further employment. In view of the array of contaminants that could be contained in a sludge sample, Moreira *et al.* (2008) proposed bioassays as a holistic way to measure toxicity.

Table 4. Protocols for content analysis by the International Organization for Standardization

Sludge characteristics	Common protocols
Content of phosphorus	Depending on sludge sample pH: • **Olsen-Phosphorus** (Olsen, 1954) • **ISO 11263:1994** - Soil quality, determination of phosphorus - spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution (ISO, 1994) • **Others** (Southern Cooperative Series, 2000)
Content of nitrogen	**ISO 11261:1995** - Soil quality, determination of total nitrogen - Modified Kjeldahl method (ISO, 1995)
Content of organic carbon	**ISO 14235:1998** - Soil quality, determination of organic carbon by sulfochromic oxidation (ISO, 1998)
pH	**ISO 10523:2008** - Water quality, determination of pH (ISO, 2008)
Electrical conductivity	**ISO 7888:1985** - Water quality, determination of electrical conductivity (ISO, 1985)
Content of heavy metals	**ISO 12914:2012** - Soil quality, microwave-assisted extraction of the aqua regia soluble fraction for the determination (ISO, 2012) **Method 6020B (SW-846)** - Inductively Coupled Plasma-Mass Spectrometry (USEPA, 2014)
Presence of *Salmonella* spp	**ISO 6579:2002** - Microbiology of food and animal feeding stuffs - horizontal method for the detection of *Salmonella* spp (ISO, 2002)
Presence of *E. coli*	**ISO 1649-2:2001** - Microbiology of food and animal feeding stuffs - horizontal method for the enumeration of beta-glucuronidase-positive *Escherichia coli* - Part 2: colony-count technique at 44 °C using 5-bromo-4-chloro-3-indolyl beta-D-glucuronide (ISO, 2001)
Presence of *Staphylococcus aureus*	**ISO 6888-1:1999** - Microbiology of food and animal feeding stuffs - horizontal method for the enumeration of coagulase-positive staphylococci (*Staphylococcus aureus* and other species) - Part 1: technique using Baird-Parker agar medium (ISO, 1999)
Viability of helminth eggs	No standard method, some possible protocols can be found in Gaspard *et al.* (1995), Rocha *et al.* (2016) and Amoah *et al.* (2018)
Ecotoxicological characterization	**ISO 15799:2003** - Guidance on the ecotoxicological characterization of soils and soil materials (ISO, 2003)
Emergent contaminants	No standard method. Díaz-Cruz *et al.* (2009) reviewed the most popular techniques for the analysis of pharmaceuticals, drugs, etc., in the sludge.

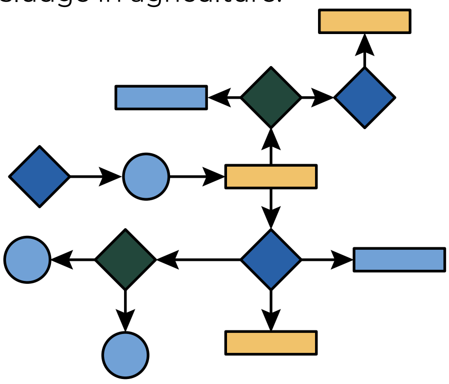
They reported germination tests and growth tests with plants, as well as avoidance and reproduction assays with earthworms and Folsomia candida (Moreira *et al.*, 2008; Fuentes *et al.*, 2004). Some guidelines for these bioassays can be also found in ISO 15799:2003, Guidance on the Ecotoxicological Characterization of Soils and Soil Materials (ISO, 2003). Farré and

Barceló (2003) also preferred combining biosensors, bioassays (plants and invertebrates), and bioluminescence inhibition with chemical-analysis protocols (i.e. solid phase extraction and chromatographic techniques) for a thorough toxicological analysis of sludge.

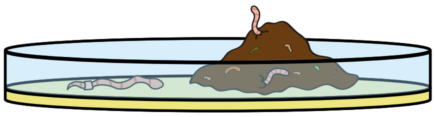
Regarding sampling protocols for sludge, the Directive 86/278/EEC of 12 June 1986 suggested the analysis of sludge every 6 months. If the characteristics of the original wastewater remain constant, this period can be expanded to 12 months.

Key messages

An all-encompasing analysis and monitoring plan are required for the safe use of sediments and sludge in agriculture.



Bioassays like avoidance tests or reproduction tests with earthworms seem most promising, as they have a holistic character and low cost.

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SECTION 6

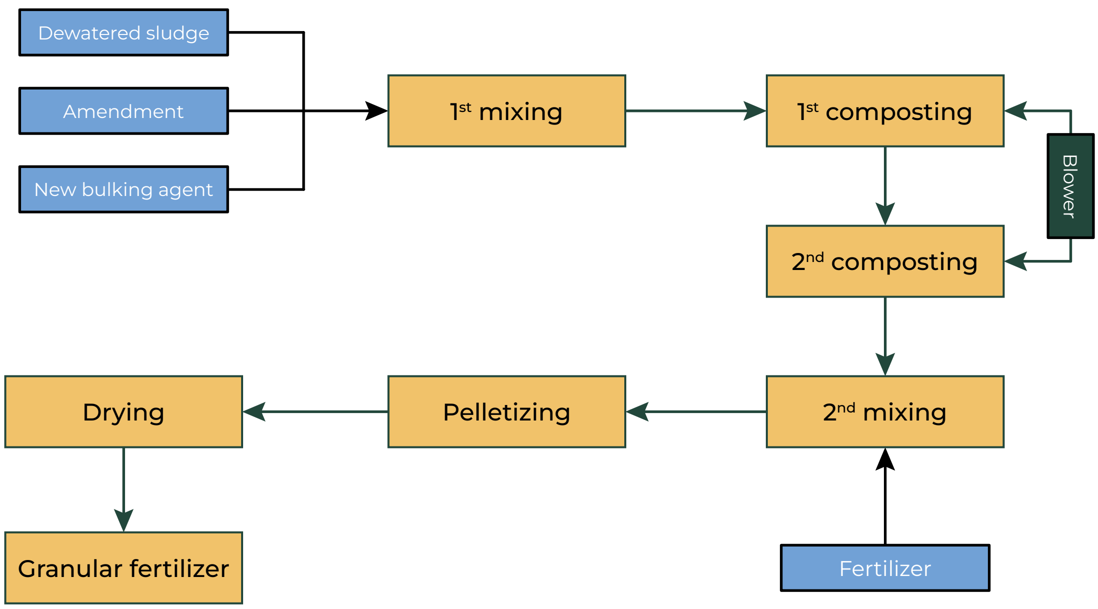
SUCCESSFUL CASE STUDIES USING SEDIMENTS AS AMENDMENTS IN CROP PRODUCTION

If the intention is to increase the reliability and safety of sediment reuse, global practices can guide national experiments through experience-sharing and method transfer. To showcase the success of real-term sediment and sludge applications, this section discusses two case studies where the application of sewage sludge and sediments for agricultural land resulted in good practices.

Composted sludge in granular fertilizers in China

The case-study was recorded by Cao *et al.* (2011) in Shenyang North WWTP, in northern China. At that time of the experiment, the average amount of generated sludge was daily 200 000 m, with average 80 percent moisture. To utilize the sludge as crop fertilizer, the Shenyang North WWTP was equipped with a sludge treatment plant to produce compound fertilizers. The sludge treatment was accompanied with the monitoring of sludge generated by 44 cities to avoid excessive heavy metal content.

Figure 18. Production process of sludge-based compound fertilizer



Source: reproduced from Cao *et al.*, 2011.

The sludge treatment process involved the observation of storage times and 70 ^{0}C temperatures, thus eliminating the pathogenic organisms and drying the sludge to decrease its moisture to 27 percent. The produced compost was applicable directly for disposal on land or for further processing as granular fertilizer. The granular fertilizer was enriched with some nitrogen, potassium or phosphate fertilizers mixed in the second mixing reactor. The final composition was adjusted to the Standards of Inorganic-Organic Compounded Fertilizers (GB18877-2002) requirements that define the proportion of nitrogen, potassium and phosphorus in the fertilizer. Finally, the mixed compost was pelletized as granules to facilitate the transport and marketing.

The case study from China represents an integrated approach with multiple application methods. Such approach could be transferred to north Lebanon as well at a smaller scale, depending on the acceptance of the community and the absorption capacity of local fertilizer industry.

Application of lake-dredged sediments to pasture lands in Florida, USA

Sigua (2009) conducted a field experiment in Sumter County, Florida (United States of America) to investigate the re-use options of lake-dredged sediments (Sigua, 2009). The experiment consisted in removing about 28 cm of natural soil and filling it back with different proportions of dredged materials, sharing from 0 to 100 percent dredged material. Each plot was then ploughed to improve the uniformity.

The experimental plots were monitored over four years after the application of sediments and cropped with bahiagrass forage. Above the rate of 50 percent of lake-dredged sediments, the soil compaction was lower. Furthermore, the application of sediments increased soil pH, total inorganic nitrogen, calcium and magnesium. In turn, total phosphorus decreased with the application of sediment. For instance, the total phosphorus of the natural soil was 6.9 mg/kg against 0.32 mg/kg when 50 percent of soil was made up from dredged sediment. The treatment proved environmentally safe, also, the heavy metals of the soil were reduced by the application of sediments. Compared to the control plot, the yields increase of sediment-amended treatment plots were 512 percent, 82 percent and 173 percent higher for the first, second and third cut respectively. Furthermore, the forage had higher protein levels.

It must be highlighted that the successful interaction between soil and sediments amendment depends on the characteristics of both. Therefore, the assessment of sediment use must be conducted together with soil analysis. In the case of Florida, the low soil pH was key for the good results obtained.

SECTION 7

CONCLUSIONS

The potential, positive impacts of sludge and sediment use as fertilizer or soil amendment appear to be consistent (Hospido *et al.*, 2005). However, in view of the complexity of its potential effects on the soil chemistry, the salinity, the human health and the environment, more long-term experiments are required (Černe *et al.*, 2019; Hossain *et al.*, 2017; Kumar *et al.*, 2017; Romanos, 2020). Heavy metals in soils could even be immobilized to prevent plant uptake (Smith, 2009; Usman *et al.*, 2006). The intermittent application of sludge has been proposed as a feasible alternative (Roig *et al.*, 2012; Singh and Agrawal, 2008).

Apart from the sludge treatment optimization, some of the research gaps are the crop-specific response to heavy metals, emerging contaminants in the soil, sludge application rates and frequencies, and leaching risks in the long term (Fijalkowski *et al.*, 2017; Seleiman *et al.*, 2020; Breda *et al.*, 2020; Kidd *et al.*, 2007). The analysis and monitoring of sludge treated soils, together with sound standards and regulations are critical to exploit the potential sediments use in agriculture. Kumar *et al.* (2017) gave distinct recommendations for developed and developing countries regarding the use of sludge in agriculture. Recommendations for developed countries suggest the abandonment of landfilling towards a controlled use of sludge in agriculture, while developing countries are recommended to promote the use of thermal processes such as pyrolysis to produce useful by-products.

General key messages

- Dredged sediment can be a useful resource in agriculture (either solely or composted with sludge or manure), construction, landscape restoration or as renewable energy.
- Dredged sediment could be used as a component for chemical fertilizers manufacture.
- The classification and separation of the different components within El-Bared sediments (MSW, fine sediments, others) is a preliminary step and a prerequisite for its safe use.
- National regulations for the use of sediments in Lebanese agriculture are desirable so that this resource may be used without compromising the human health and the environment.
- Previous characterization of the sediment (nutrients, pollutants, pathogens, etc.) and its source is required before planning its potential uses.

- Soil analysis (physical, chemical and biological properties) and soil monitoring must be conducted before applications so as to predict the interaction with the sediment.
- The classification of crops for sediment use prevents contaminants from going into the food chain. In the case of Lebanon, use in tree crops may be recommended, such as olive trees.
- Ambitious monitoring plans are needed if sediments are applied over the long term, including monitoring the accumulation of heavy metals in the soil as well as the possible changes in soil properties.
- In view of the plethora of potentially hazardous components, a holistic bioassay as the avoidance and reproduction tests with earthworms can be an interesting option.

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Rapid urbanization is stretching natural resources and leading to an environmental degradation in many regions.

In the Governorate of Akkar, in the north of Lebanon, there has been a recent sharp population increase, placing a heavy strain on both fresh and marine water resources. The adverse effects of contamination are further exacerbated by the sediment deposited on the canal bottom, which also carry a large amount of pollutants.

This report provides an insight into sediment collection and use strategies that can be transferred to El-Bared irrigation system by providing an overview of global and national practices of sediment application; setting the theoretical baseline for the implementation of these practices; and paving the way for scalable pilots in the country.

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