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ORIGINAL ARTICLE

# Techno-economic evaluation of biofertilizer production using wastewater biosolids: case study from municipal wastewater treatment plants in northwest region of Russia

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## Abstract

The continuous and rapid growth of sewage sludge (biosolids) from wastewater treatment plants (WWTPs) poses both economic and environmental challenges. In many cities of Russia, the situation has exacerbated with time. In this study, three state-of-the-art biosolid management technologies, namely windrow composting (WC), tunnel composting (TC), and lime stabilization (LS), were evaluated for their economic feasibility to produce commercially biofertilizers from WWTP-derived biosolids. Based on an annual discharge of 22,000 $m^3$ of dewatered biosolids from the case WWTP, about 29,785, 22,453, and 35,056 $m^3$ biofertilizers could be produced through WC, TC, and LS, respectively. Analysis showed the selected WC, TC, and LS technological options to be feasible if the selling price of the produced biofertilizer would be maintained at 19 EUR/$m^3$ for WC and LS, and 77 EUR/$m^3$ for TC. The discounted payback period (DPP) of WC, LS, and TC would be 3.1, 18.1, and 25.3 years, respectively, with an IRR (internal rate of return) of 10%. The key characteristics of the treated WWTP-derived biosolids were found to be good enough to meet the existing environmental laws, standards, and regulations in Russia. From an investment perspective, this study is useful in developing WWTP-derived biosolids for biofertilizer production at enterprise level.

**Keywords** Techno-economic evaluation · Wastewater biosolids · Composting technologies · Lime stabilization · Biofertilizer production

## Introduction

Growing global population and rapid urbanization, together with other anthropogenic activities and climate change impacts, are putting tremendous strain on the limited water resources [1], thereby causing serious degradation of the quality and quantity of the resource [2]. Wastewater refers to 'used water' that can be discharged from agriculture, households, hospitals, business, factories, cities, industries, or any other structure where water is used [3]. About 80% of the global wastewater is released into the natural environment without adequate treatment [4]. Wastewater contains various effluents, including a heterogeneous mixture of microbial, organic, inorganic, and other hazardous substances. Direct usage of wastewater imposes a serious risk on the health and vitality of living organisms, including humans, plants, animals, and their environment [5]. Wastewater treatment is the process of improving the quality of water by subjecting it to certain physical, chemical, and biological processes to separate suspended solids, various wastes, and other harmful chemicals from a liquid effluent stream either for re-use or discharge into an ecological system; solid–liquid streams of debris and sludge are generated as by-products [6]. Thus, producing reclaimed or recycled water at wastewater treatment plants (WWTPs) is steadily evolving and becoming an inevitable part of city development plans across the globe as a sustainable solution to face the challenges with water-stressed and scarcity [7].

In terms of renewable water resources, Russia is the second-largest country after Brazil. The mean annual renewable water resources in the country are about 4324 billion $m^3$/year [8]. The freshwater consumption of the country

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is estimated at about 61.4 billion $m^3$/year, of which 63% is accounted for industrial-economic water use, 22% for municipal water use, and 15% for agricultural water use [8]. A recent study showed that every year about 10 billion $m^3$ of wastewater is discharged from Russian Municipal WWTPs, leaving about 80 million $m^3$ of sewage sludges, 80% (60 million tons) of which consists of biosolids [9, 10]. Growing volumes of sewage sludges (biosolids) from WWTPs pose both economic and environmental challenges for many local municipal authorities in Russia. Besides, storing biosolids in open lands produce a variety of gaseous products such as methane through the natural process of bacterial decomposition of organic waste under anaerobic conditions. Methane is a more powerful greenhouse gas than carbon dioxide, and its emissions escalate the level of greenhouse gasses in the atmosphere [11].

Typically, biosolids are nutrient-rich organic materials—they contain a significant amount of nitrogen, phosphorus, potassium, a small quantity of many plants' essential micronutrients, such as zinc, sodium, and molybdenum, and other valuable elements that make it possible to recycle them beneficially as fertilizers or soil amendment agents [12]. Recycling of WWTP-derived biosolids to produce biofertilizers for soil improvement, agricultural crop production, rangeland, urban landscape, home gardens, and land reclamation has been practiced for several decades in many developed countries of the world [13–15]. This practice is regarded as a sustainable and integrated circular system as well, as one of the best disposal solutions in many European countries [16]. However, in Russia, most of the biosolids from WWTPs are not used as raw material for producing new products and are typically dumped and placed in landfills. This phenomenon is common in many parts of Russia, mainly due to the lack of available adequate techno-economic solutions [17].

Until now, the techno-economic data on WWTP-derived biosolids for biofertilizer production in Russia to support the sustainable management of these resources either at the local or regional levels are very limited. Data on analysis of biofertilizer production from WWTPs-derived biosolids by adopting different composting technologies are still absent in the country. A detailed economic analysis with possible operational and recurrent costs and other factors of different biosolid treatment methods is crucial to scale up the resources at an enterprise level. Moreover, the orientation of technology and operational costs, in the case of WWTP-derived biosolid management, are highly relevant [18]. This research is the first ever to evaluate techno-economic feasibility for recycling WWTP-derived biosolids to produce biofertilizers in Russia.

Biosolids may be stabilized through modern aerobic and anaerobic digestion, and heat treatment [19]. However, these are often subjected to energy-intensive, higher amount of $CO_2$ emissions [15] as well as associated with intensive maintenance operation throughout the whole biosolids handling systems [20]. On the other hand, composting is becoming a popular method for handling biosolids because it is an inexpensive, simple, and environmentally friendly process [21]; it has been successfully used for several decades in many countries [22]. Apart, the stabilization of wastewater biosolids using lime is another simpler and cost-effective method, and is widely applied in many developed countries, including the USA [23]. In this study, we investigated the three state-of-the-art wastewater sludge (biosolid) management technologies, namely windrow composting (WC), tunnel composting (TC), and lime stabilization (LS) (often called lime treatment (Lt.)), and evaluated their techno-economic feasibility. The novelty of this research is that it highlights the various economic indicators (i.e., production cost, selling prices, operational costs, sensitive analysis of WWTP-derived biosolids to biofertilizer production) and provides scientific data on the quality of the treated biosolids for biofertilizers production. Moreover, we evaluated the key characteristics (i.e., heavy metals, nutrient values) of the treated biosolids from two WWTPs located in the northwestern region of the Russian Federation to know their quality and standards for the production of biofertilizer for agricultural use. The information produced from this study can act as a decision support tool to help select an appropriate technology from the available options and avoid risk to future investment dealing with sustainable wastewater sludges and biosolid management. The findings of this study can help policymakers, various entrepreneurs, investors, scientific communities, governmental organizations, non-governmental organizations, international organizations, and other relevant stakeholders with the development of WWTP-derived biosolids for biofertilizer production at commercial scale/enterprise level in many parts of the Russian Federation and other countries with a similar environment.

## Overviews of case WWTP and target product

### Overview of the case WWTPs

The case study took place in two WWTPs, one in Petrozavodsk and another in Sortavala. Both are located in the Republic of Karelia of the Russian Federation. The case 1 (Petrozavodsk)-WWTP is situated on the western shores of Lake Onega, which falls in the catchment area of the Baltic Sea. The WWTP was commissioned in 1979; presently, the plant belongs to a company limited by shares. It provides sewerage services for a population of over 250,000 people. Annually, about 22,000 tons of municipal wastewater biosolids are discharged from the observed case 1-WWTP. The biosolids are often dumped in landfills near the premises of the plant. In practice, before dumping, the biosolids are treated at mechanical, biological, and chemical units. The biosolids mainly arise from both preliminary and secondary sludge traps. In the preliminary sludge trap, the biosolids come after wastewater treatment with screen and grit removal, and in the secondary sludge trap, active sludge is generated during biological purification in the aeration tanks. After the sludge traps, a mixture of the biosolids goes to the mineralizer, where the sludge thereafter is subjected to mechanical sludge dehydration for dewatering.

During this process, a flocculate is added to reduce the biosolids' moisture content by up to 70% of their volume. When the dewatering is complete, the biosolids are then transported to the lagoons by trucks, which incurs a high operational cost for the treatment plant. The biosolid lagoon is a concrete reservoir, with dimensions of $40 \times 80 \times 2.5$ m. In the lagoons, the biosolids are kept for 3 years, where dehelminthization (i.e., elimination of helminth eggs) takes place. Hereafter, the biosolids are deposited in landfills.

The case 2 (Sortavala)-WWTP is in the Sortavala Bay area which is located in the northmost part of Lake Ladoga. The WWTP is loaded with wastewater from human settlement and industry in the Sortavala town. Two-third of the town where about 20 000 inhabitants are connected with the plant and from there the discharges are fed to the WWTP where mechanical and biological treatment takes place. The outlet of the WWTP is laid to the Lake Ladoga. Annually, about 6000 tons of municipal wastewater biosolids are discharged. The collection patterns of WWTP-derived biosolids are almost the same as observed in case 1-WWTP, however, in case 2-WWTP, a LS facility has been installed to produce biofertilizers from wastewater biosolids.

In recent years, the case WWTPs were often faced with a daunting challenge to acquire land for disposal of the sludges and biosolids, and the situation is anticipated to worsen soon. Currently, there is no clear option that can handle the problem of the existing sludges and biosolid volume management effectively and in an environmentally friendly manner. Thus, there is an urgent need to find a realistic approach that can address the current situation of sludge and biosolids production, management, and disposal.

### Selection of target product

Biosolid-based products from wastewater sludges vary depending on the purpose as well as the end usage. Hence, it is important to determine the target product that would help narrow down the available technological options and provide comparatively better economic benefits and environmental sustainability. According to the Russian standards [24], biosolids from WWTPs can be utilized for producing several types of products, and one of them is compost or so-called "soil improver/biofertilizer". As per the standards, the production of compost from biosolids does not need an agrichemical certificate, but for the other product types, such as agricultural chemicals, the certificate is required. However, in the case Karelian region of the Russian Federation, the demand for the selected WWTP-derived raw compost for use in gardening and landscaping is known to be steadily increasing. An estimated amount of 44,000 $m^3$ of it is used annually mostly for improving the topsoil. Although recycled biosolids for producing biofertilizers are environmentally friendly and encouraged for agricultural and urban landscaping purposes, the case WWTP-derived biofertilizer is yet not available in the market.

In the case study area, the price of WWTP-derived raw compost material is rather cheap in comparison to chemical and other bio-based fertilizers. Currently, the price varies between 3 and 9 EUR/$m^3$ depending on the quality of the raw material. The raw sludge and biosolids are often poor in quality because of mineral deficiency, handling inconvenience, and restricted use in agriculture fields or for any other similar purpose as per the national legislation of the Russian Federation. Biosolid-based biofertilizer improves soil quality by enhancing the physical, chemical, and biological properties [25]. It also improves the soil's tilth, water-holding capacity, stability, and air–water transport, and it can ultimately decrease soil erosion [13]. Considering these advantages, biofertilizers are selected as the target (final) product of recycling biosolids in the case WWTP.

## Materials and methods

### Sources and collection of data

The research was carried out through intensive field visits coupled with interviewing several experts. The biosolids raw material flow to biofertilizers production through WC, TC, and LS methods was gathered from interaction with experts from several specialized companies, namely Joint Stock Company Petrozavodsk Communal Utilities Systems—JSC PKS-Vodokanal of Russia, Limited Liability Company—Karelvodokanal of Russia, Ecolan Oy, Metsä-Sairila Oy, and HSY Oy of Finland, and Sodimate Ltd. of Germany. In addition, physical field visits to the wastewater treatment plant sites were carried out as well as several literature [23, 26–30] were explored to analyze and validate the data. However, the data on the current generation of sludge and biosolids, composting processes, applied aggregates, and equipment were collected through personal communication with the case WWTP's managers and operators. Other relevant data, such as the current use of biosolids, their processing for biofertilizer production, usages of WWTP-derived biomaterial for landfilling applications, their prices and marketing, annual demand, and the impact of end-user application were gathered through informal interaction and consultation with several informants such as from households, communal authorities, research organizations, and industry associations. The parameters, performance indicators, and guidelines for the WC, TC, and LS methods were synthesized by interviewing several experts from specialized companies, for instance, Metsä-Sairila and HSY WWTPs of Finland, Waste Treatment Technologies of Netherlands, and Sodimate WWTP of Germany. The data on the performance of the machines, which are needed to carry out the processes of the selected methods, were extracted from the technical and operation data cards, as well as consultations with the relevant operators and experts.

## Selection of technologies

As mentioned earlier, biofertilizers from WWTP-derived biosolids can be produced quite often through composting and LS technologies. Composting is a biological process that degrades organic materials under controlled aerobic conditions; this process is widely used to stabilize wastewater biosolids [27]. Composting solutions are available in the market, ranging from a simple and traditional windrow-based approach such as WC, which requires little effort in terms of process structures, to a complete enclosure with a high-quality treatment of exhaust air, often referred to as TC [26]. Hence, WC and TC were chosen as convenient methods for composting. Notably, the LS method is relatively a cost-effective process for wastewater biosolid stabilization. This method consists of a simple procedure that needs mixing of biosolids with hydrated lime [$Ca(OH)_2$] or quicklime (CaO), with special equipment for reliable operation [23]. For convenient mixture making, a fixed indoor installation on the WWTP or portable aggregates is available in the market. Thus, the LS method was also considered for techno-economic analysis under this study framework.

## Process design and input data

To implement WC and TC, several batch operations must be done (Table 1). For each operation, a specific machine is required that varies in terms of its performance and expenditure. It was also assumed that the recipe of the target product comprises 50% of stabilized biosolids and the rest is sand, peat, or other relevant material, which does not contain any seeds of weeds. The expenditure observed during our analysis was originally in Russian rubles (RUB) and was converted into EUR at a rate of 73 RUB/EUR.

On the other hand, LS operation is a rather automated process and is performed through a set of treatment lines. The treatment operation requires certain equipment, including a silo for quick lime, discharge and metering unit, conveyor, lime injector, sludge screws, and sludge/lime mixer. However, LS does not require any complicated technical operations except for mixing of treated biosolids with mixing substances such as sand and/or peat to make the target product (i.e., biofertilizer). Thereafter, the mixture is processed in the same way as in composting. However, the cost involved is mostly related to the volume of raw biosolids that the machines serve (Table 2). The loss of volume of biosolids depended on the mass flow available at the WWTP, for commercial utilization by the companies dealing with composting and LS technologies. Notwithstanding, a set of standard doses were considered while analyzing the stabilization of biosolids using LS (Table 3). In practice, the volume of the target product (i.e., biofertilizer) depends on the DS (dry solids) content (i.e., moisture content) and the final bulk density [31]. In WC and TC, water addition is important; however, the cost for this was not considered in our calculation since it is rather small.

**Table 1** Technical details (machine, performance, and relevant cost/expenditure) of WC and TC technological operations

| Operations | Machine | Output ($m^3$/hour) | Cost (EUR/hr) | Windrow c | Tunnel c |
|---|---|---|---|---|---|
| 1. Loading BS[a] onto the truck | Loader | 50 | 44 | × | × |
| 2. Transfer of BS to the operating site | Truck | 25 | 28 | × | × |
| 3. Delivery of WCh[a] to the operating site | Chip truck | 27 | 40 | × | × |
| 4. Mixing BS and WCh | Front loader | 150 | 44 | × | × |
| 5. Loading mixed BS and WC to the tunnel | Front loader | 180 | 44 |  | × |
| 6. Screening, returning WCh to the process | Drum sieve | 40 | 44 | × | × |
| 7. Forming windrow | Front loader | 180 | 44 | × | × |
| 8. Turning windrow | Front loader | 180 | 44 | × | × |
| 9. Mixing BS with sand and/or peat, target product | Front loader | 150 | 44 | × | × |

[a] *BS* biosolids, *WCh* woodchips

[b] Screening in the WC option is performed before Stage 9

**Table 2** Annual volume flow and input materials for processing of biosolids using WC, TC and LS technological options

| Inputs | Windrow c. | Tunnel c. | Lime sta. |
|---|---|---|---|
| Dewatered BS, $m^3$ | 22,000 | 22,000 | 22,000 |
| WCh[a], $m^3$ | 22,000 | 66,000 | – |
| CaO, $m^3$ | – | – | 657 |
| Electricity, kWh | – | 2,000,000 | – |
| Stabilized BS, $m^3$ | 14,892 | 11,227 | 20,412 |
| DS, % | 65 | 65 | 30 |
| Density, $t/m^3$ | 0,60 | 0,61 | 1,05 |
| Sand, $m^3$ | 7446 | 5,613 | 20,412 |
| Peat, $m^3$ | 7446 | 5,613 | – |
| Target product, $m^3$ | 29,785 | 22,453 | 35,056 |

Note: [a]Each year, 20% extra chips need to be added due to losses during the screening procedure

**Table 3** Standard amount of quicklime (CaO) to be mixed with biosolids using LS technological option

| Initial sludge (% of DS) | CaO quantity (kg)/kg DS |
|---|---|
| 15% | 0,7 kg |
| 20% | 0,5 kg |
| 25% | 0,4 kg |
| 30% | 0,2 kg |

## Economic analysis

The life cycle cost assessment (LCCA) methodology was used to evaluate the techno-economic aspect of WC, TC, and LS for the selected WWTP in Russia. The several assumptions described in Tables 1and 2 were considered for the evaluation. In our analysis, an operating life (depreciation) of 15 years was considered for each technological option. The first year was dedicated to the construction and start-up work, and the subsequent years were for the operation of the technological option at the rate of 8 h/day, 300 days/year; all processes were assumed to be based on batch operations.

Regarding the economic analysis, the costs related to raw biosolid processing, input materials, and power consumption for the treatment of biosolids to produce biofertilizers were considered. The cost for production of dewatered biosolids from raw biosolids was 0.04 EUR/$m^3$, assuming that the dewatered biosolids have an initial density of 1 $t/m^3$. The cost of other input materials such as wood chips, quicklime, and sand/peat was 15 EUR/$m^3$,753 EUR/$m^3$ and 6 EUR/$m^3$, respectively. All materials' cost was included in the delivery cost. The electricity cost was 0.06 EUR/ kWh. The labor cost was 2871 EUR/month (one supervisor and four guards) for WC and LT methods, and 5190 EUR/month (one supervisor, two maintenance, one cleaning person, and four guards) for TC.

The total CAPEX (capital expenditures) at site depended on the information provided by the commercial offers of the case WWTP. Indeed, WC requires no specific installation except operational site construction. In our observed WWTP, an asphalt-based yard was planned, with an area of 1280 $m^2$. The local price for the asphalt laying was 10 EUR/$m^2$, so the total CAPEX at site for WC was assumed to be 12,800 EUR. However, TC requires, comparatively, a larger investment in the construction of composting tunnels, halls, a driving aisle, and biofilters. In addition, the cost related to process equipment and odor abatement interventions need to be considered. An asphalt-based yard also needs to be constructed, and the cost of it is the same as for WC. Thus, the total CAPEX at site for TC was estimated at 6,580,800 EUR. For WC and TC, the CAPEX at ex-site was estimated at 8,333 EUR for buying/leasing of equipment and construction trailers that are absolutely needed for the compost-making process. However, for LS, the total CAPEX included the cost of equipment, input material, installation, start-up, and adjustment work, which altogether amounted to 94,250 EUR. Annual maintenance of 5% of the total CAPEX was considered at site for each biosolid treatment method.

Moreover, the net present value (NPV), internal rate of return (IRR), and discounted payback period (DPP) are important parameters for making investment decisions. The most straightforward discounted cash flow measure of a project worth is the NPV. The NPV is the difference between the present value of all cash incomes and the present value of all cash outflows. For this parameter, the following formula was applied:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

where $C_t$ = net cash flow during the period t, $C_0$ = total initial investment cost, t = number of time periods (years), and r = discount rate.

On the other hand, the IRR is a discount rate that makes the NPV of all cash flows from a project or investment equal to zero. The calculation of IRR uses the same formula as that of NPV:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 = 0$$

However, the target product has not become available in the Russian market yet. As such, the core of the economic evaluation is needed to find out the minimum selling price for the target product; the investment is considered desirable if the NPV becomes positive and the IRR is placed at around 10%, as it is the most reliable and acceptable rate of return. These were taken into account in our economic evaluation.

The DPP is a capital budgeting procedure that is used to determine the profitability of a project. A discounted payback period gives the number of years it takes to break even from undertaking the initial expenditure, by discounting future cash flows and recognizing the time value of money. It was calculated using the following formula:

$$DPP = A + (\frac{B}{C})$$

where A = the last period with a negative discounted cumulative cash flow, B = absolute value of the discounted cumulative cash flow during period A, and C = discounted cash flow during the period after A (in which the cumulative cash flow is = > 0).

### Determination of key elements of WWTP-derived sludge

Sewage sludge (biosolids) samples were collected from the biological unit of the case 1 and case 2 WWTPs. The samples were kept in the oven at 105 ℃ for 12 h until air dry. Afterward, the sludge was ground to obtain analytical grain (RETSCH S1000 ball mill) and digested. Sludge pH was determined by the potentiometric method in 1 mol/dm$^3$ KCl solution using pH-meter Mettler Toledo Delta 350. To determine the amount of heavy metals (HMs), our study followed standard procedure —U.S. EPA Method 3051A (SW-846): Microwave Assisted Avid Digestion of Sediments, Sludges, Soils and Oils. About 250 mg of dried sludge sample was digested with 6 ml of $HNO_3$ and 1 ml of $H_2O_2$ and placed in fluorocarbon microwave vessels. Each group of sample vessels was capped and irradiated for 10 min. The sample vessels were placed in a microwave oven (MARS 5- CEM) for 10 min with a temperature between 170 and 180 ℃. After cooling, the vessel samples were filtered. About 7 ml of filtered samples were placed in each flask, and then diluted the samples with Milli-Q water to raise the volume at 25 ml. Afterward, the samples were placed in a suitable inductively coupled plasma optical emission spectroscopy (ICP-OES) for analyzing the amount of HMs.

However, in this study, some key parameters such as MC (moisture content), the amount of N (nitrogen) in % of DM (dry matter), TP (triphenyl phosphate), and TOC (total organic carbon), K (potassium), Pb (lead), Cd (cadmium) Ni (nickel), Cr (chromium), Zn (zinc), Cu (copper), and Hg (mercury) of sludges were analyzed by following standard procedures. To determine the amounts of N and C in sludge, the samples were kept in an oven at 40 ℃ for 12 h for drying. About 250 mg of samples were put in each polytetrafluoroethylene vessel and placed at Elementar-Vario Max Cube for the analysis. The results of the analyses for all HMs and the key parameters were based on the average value calculated with a minimum of triplicate assays. All laboratory works for the analyses were performed at the School of Forest Sciences, University of Eastern Finland.

## Results and discussion

### Process analysis of selected technologies

Windrow composting (WC) has been recognized as one of the simplest methods for treating wastewater biosolids to produce a marketable product that is humus-like, without detectable pathogens, and can be used as a biofertilizer. In this method, biosolids are mixed with carbon-rich materials and placed into a windrow for anaerobic microbial decomposition to stabilize organic wastes (Fig. 1). The key aspect of the method is to promote the biological activity required for accelerating composting processes; hence, the appropriate mixture of carbon (C), nitrogen (N), water ($H_2O$), and oxygen ($O_2$) is necessary. Typically, a C:N ratio of 30:1 is suitable for composting [28]. Biosolids often contain a high amount of N; hence, large amounts of carbon-rich materials such as wood chips must be added to achieve the correct proportion. Normally, 40–50% by volume of woodchips is

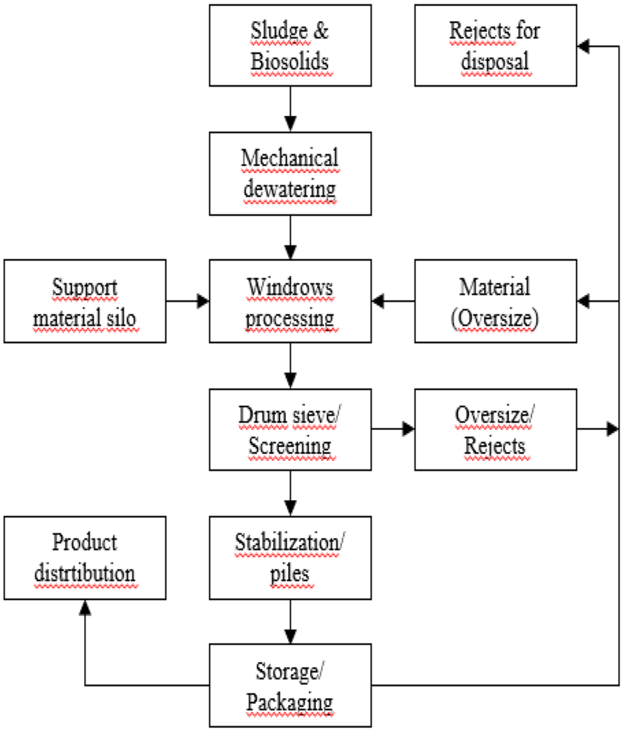

**Fig. 1** Flow diagram of a windrow composting (WC) facility for sewage sludge/biosolids to produce biofertilizers

mixed with the raw biosolids. A moisture content of 45–60% is considered desirable [32]. To keep the process aerobic, the windrow should be porous enough to allow fluxing $O_2$ in and $CO_2$ out. For this, wood chips of more than 2 mm in dimension can be used [33].

A WC site must be adequately lined with concrete, asphalt, or any other relevant base. The site should be slightly sloped (1–3% slope) and it should be located far enough from any surface watercourse. The availability of water access and irrigation equipment is ideal for the composting process. After compost maturation, the woodchips are separated from the composted biosolids and recycled back to the next windrow using a screening machine. Due to the loss of volume during this procedure and acceleration of the microbial activities, it is necessary to add 20–25% extra woodchips at each successive composting stage [31]. Since WC requires a moist environment and the presence of $O_2$, the composted biosolids must be aerated by turning the windrow once every 2 to 4 weeks. This can be done using specialized compost turning equipment or front-end loaders. Turning the compost actively and efficiently must be continued until the compost becomes matured. Often, this takes about 6–12 months depending on the degradability rate of the biosolids [31]. The investment cost for WC mainly depends on the plant's size, capacity, and operational efficiency of the turning machines, machine handling, and transportation of raw biosolids materials to the composting site. As implied, the WC process does not require electrical power or additional chemicals.

Tunnel composting (TC) is one of the popular methods used for the stabilization of WWTP-derived sludge and biosolids for biofertilizer production. This method enables the operators to maintain closer control of the processes. In TC, bacterial decomposition occurs in constructed containers (tunnels) that are provided with ventilation systems through a floor plenum, internal air circulation, and biofilters. A mixture of biosolids is loaded into a tunnel using front-loaders or conveyors (Fig. 2). To aerate the mixture, the air is blown into the tunnel through augers, conveyors, rams, or other devices. The biosolids are kept inside the tunnel for 1–2 weeks. After active composting, the intermediate compost is discharged from the opposite end of the tunnel. The intermediate compost is then stored in a pile for additional curing. Thereafter, the intermediate product is placed for processing through the windrow for final maturation and stabilization. This method takes about 22–24 weeks to get the target product, that is, a biofertilizer [34], which is about 2 months less than that required by WC. However, TC requires larger investments as compared with WC. Apart, this process requires about 100 kWh energy in the form of gasoline, electricity, and heat, (i.e., for tractor operation, tunnel equipment operations, and drying) to process 1 ton of biosolids to biofertilizer production. However, no chemical is needed for TC.

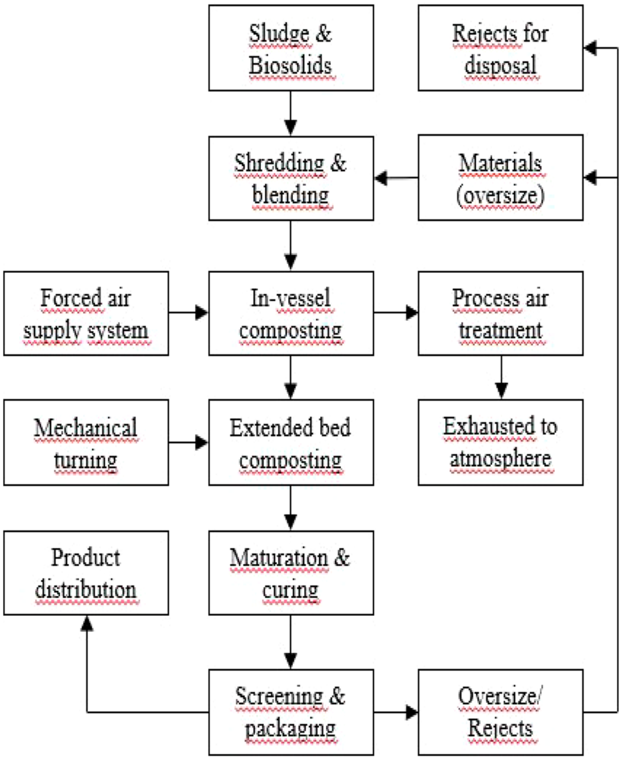

**Fig. 2** Flow diagram of a typical tunnel composting (TC) facility for sewage sludge/biosolids to produce biofertilizers

Apart from WC and TC, lime stabilization (LS) is another simple, popular, and low-tech method for the stabilization of WWTP-derived sludge and biosolids (Fig. 3). In this method, adequate CaO is used as a flocculating agent to achieve a desirable pH of more than 12. The CaO is mixed with dewatered sludge in a closed mixer for a very short period (only 20–30 min) to increase the temperature of the slurry, where CaO reacts with biosolids. Thereafter, the pH of the slurry increases above 12, which creates an environment to stop or considerably decrease the reactions of microorganisms, reduce hydrogen sulfide generation, metal leachability and attraction of different vectors [35, 36]. Most LS facilities in Russia have the freedom to select the doses of CaO according to the sludge (i.e., biosolids of Grade I or Grade II) regulations suggested by Russian standards [37]. To meet the criteria, the pH of the sludge must be more than 12 for 2 h, with a combined temperature between 60 and 70 ºC for 30 min. The LS method is reported to play an important role in decreasing the pathogen content of the biosolids, accessibility of heavy metals, and the associated environmental risks, as well as enhancing its usage in agricultural purposes [30].

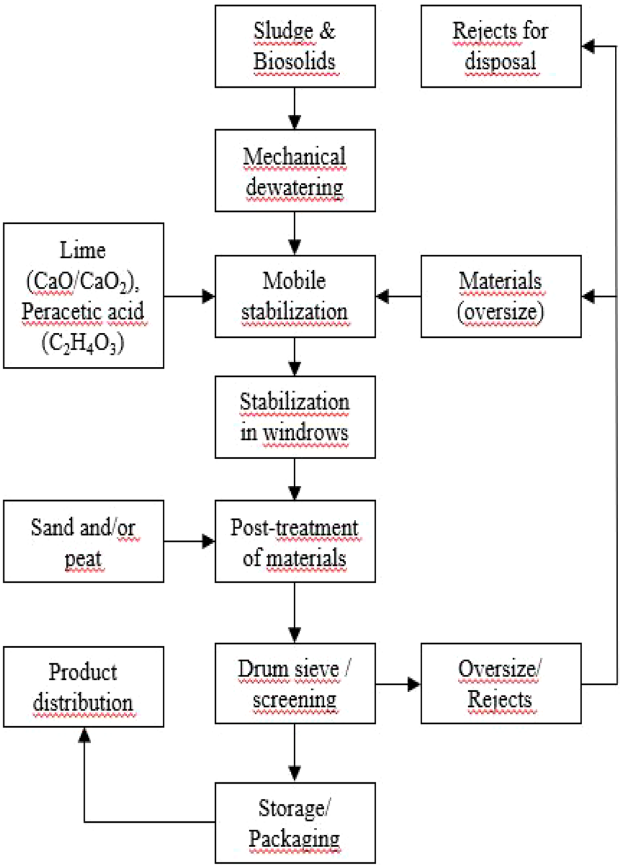

**Fig. 3** Flow diagram of a lime stabilization (LS) facility for sewage sludge/biosolids to produce biofertilizers

Biosolid stabilization through LS has been suggested as an advanced treatment application for sludge management by the EU [38]. This procedure is comparatively a cost-effective option, with lower capital costs than that of many other treatment options [30]. The investment costs mostly depend on the quantity of biosolids to be treated. The lime consumption in this process is the main contributor to the incurred cost. The minimum and maximum consumption of lime are decided on a case-by-case basis depending on the type and dryness of the solid content of the biosolids. The technical lifetimes of the equipment used in WC, TC, LS were considered to be about 20 years.

Our study estimated that the annual production of biofertilizer from biosolids in the case WWTP would be 29,785 $m^3$, 22,453 $m^3$, and 35,056 $m^3$ using WC, TC, and LS, respectively. The estimations were based on the annual generation of 22,000 $m^3$ of dewatered biosolids and its mass flow during the stabilization process, as well as the proportion of mixing materials such as sand or peat with dewatered biosolids as 50/50.

## Economic evaluation of selected technologies

Figure 4 corresponds the operational costs for production of biofertilizer from wastewater biosolids using WC (A), TC (B), and LS (C). The average operating costs for biofertilizer production using WC were identified as the cost of batch operations, which accounts for approximately 61.4% of the total operating costs, followed by the cost of extra material to be mixed with the maturated biosolids (17.3%), processing of materials during maturation process (14.8%), labor (6.4%), and maintenance (1.8%). For TC, the major costs incurred were for maintenance (37.2%), batch operations (29.5%), and process materials (15.1%), and extra material for target product (7.9%), labors (7.0%), and electricity (3.1%). The LS method seems to be rather simpler regarding the needs for batch operations (1.6%) and maintenance (0.6%), but it requires a substantial cost for processing the materials (75.9%) and materials stabilization (16.6%); an additional minor cost for labors (5.1%) and electricity (0.1%) is also incurred (Fig. 4). The screening and turning operations are the most expensive stages in the batch operations for WC and TC, while LS seems almost free of them, except

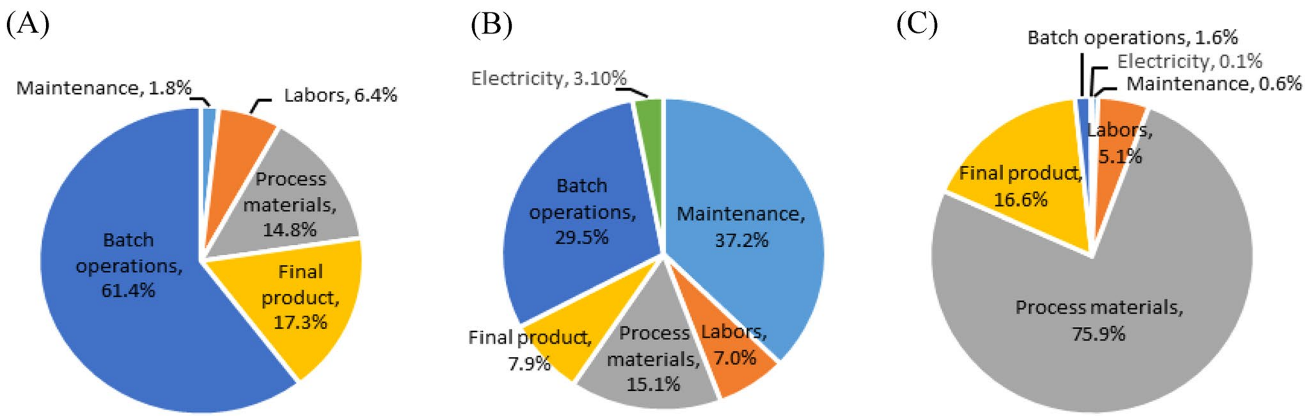

**Fig. 4** Operational costs for production of biofertilizer from wastewater biosolids using WC (**A**), TC (**B**), and LS (**C**) technological options

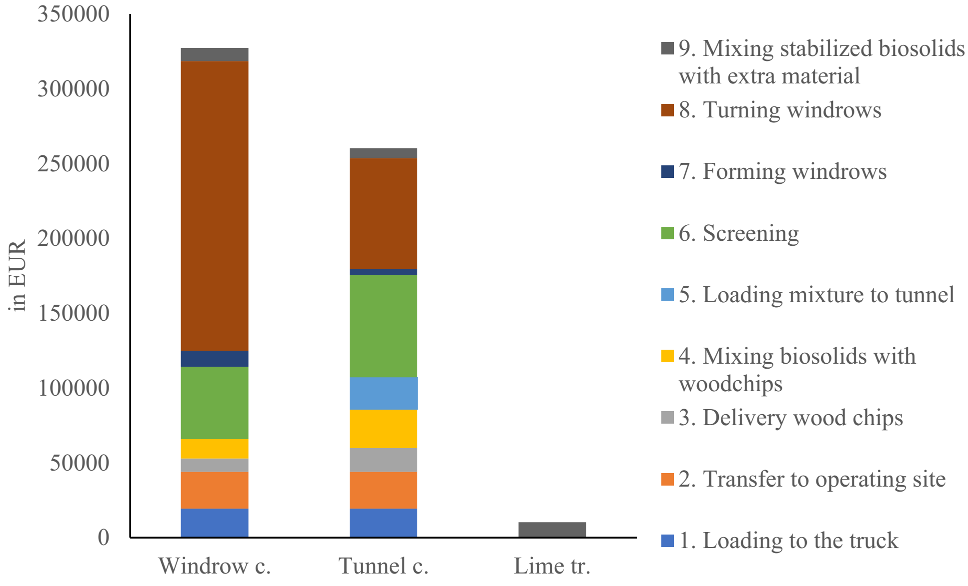

**Fig. 5** Breakdown of batch operation costs for production of biofertilizer from wastewater biosolids using WC, TC, and LS technological options

for the cost to mix stabilized biosolids with extra material for stabilization (Fig. 5). The annual biofertilizer production cost through WC, TC, and LS was calculated to be approximately 538,133 EUR or 18 EUR/m$^3$, 897,894 EUR or 40 EUR/m$^3$, and 652,035 EUR or 19 EUR/m$^3$, respectively, excluding the cost of marketing and packaging (Fig. 6). Typically, the cost of marketing and packaging can be increased by about 10% of the production cost [34].

The economic analysis showed a fully negative NPV for the above-mentioned technological options to produce biofertilizers from wastewater biosolids if the selling price for the produced biofertilizer is the same as the topsoil (Fig. 6). The market price of topsoil (landscaping soil) was observed to be around 9 EUR/m$^3$, and topsoil was available in local markets in the case area. Nevertheless, the analysis showed that the NPV started to become positive (i.e., 0 EUR) if the selling price of the produced biofertilizer was 19 EUR/m$^3$ for WC and LS and 77 EUR/m$^3$ for TC. It indicated that the investment would be justified if the WWTP-derived biosolids are processed for biofertilizer production using WC and LS, with a minimal selling price (e.g., 19 EUR/m$^3$) and comparatively lower CAPEX. However, the DPP of WC, TC, and LS were estimated to be 3.1, 25.3, and 18.1 years, respectively, with an IRR of 10%.

Considering all operational costs, the sensitivity analysis showed that the key to success in biofertilizer production with composting approaches and LT depended on the quantity of target product (e.g., biofertilizer) and the base selling price of the product. The sensitivity analysis also showed that the NPV significantly changes as these two parameters increase or decrease. In WC, when the target product amount and price change fall within a range of

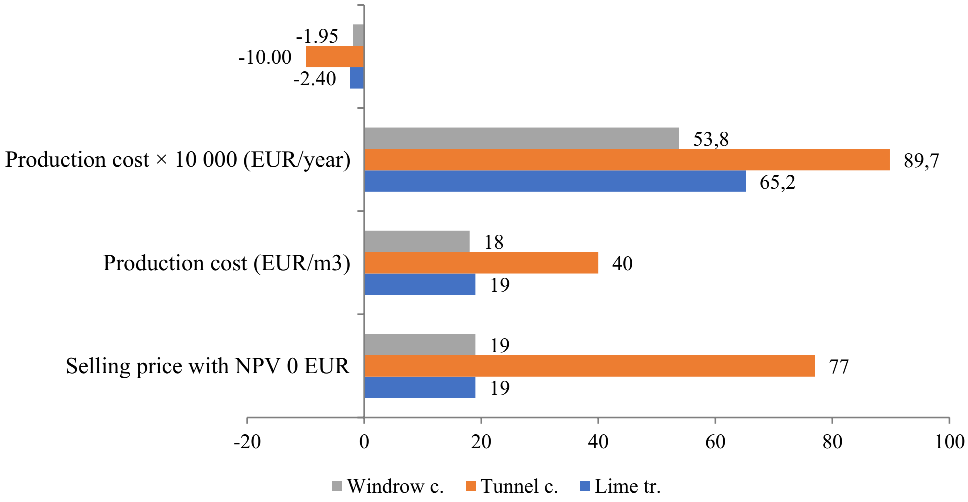

**Fig. 6** Selling price (top left bars) at current level, production cost (second and third right bars) and proposed selling price (below right bars) of produced biofertilizer from wastewater biosolids using WC, TC, and LS technological options

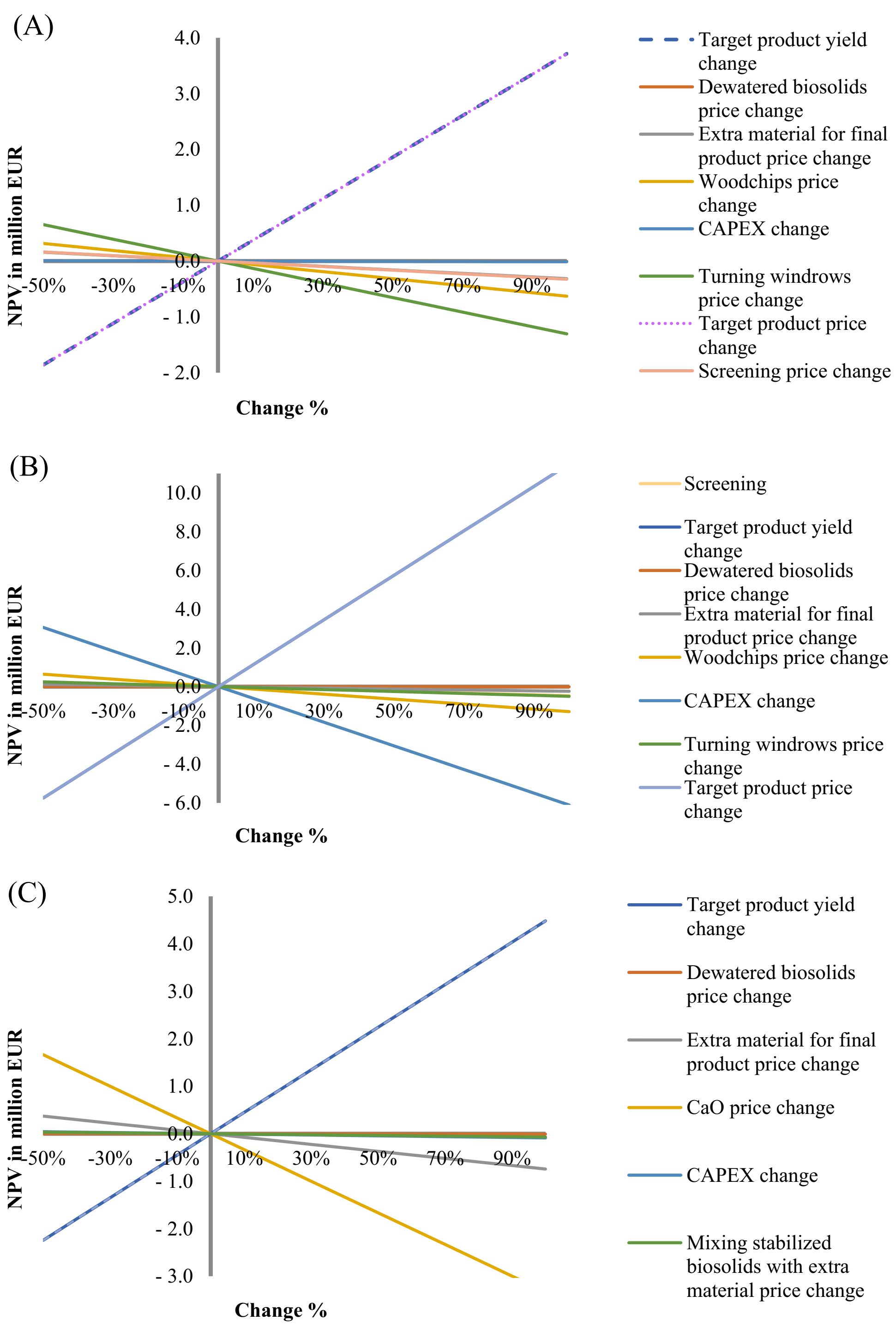

**Fig. 7** Sensitivity analysis based on NPV of biofertilizer production from wastewater biosolids using WC (**A**), TC (**B**), and LS (**C**) technological options

− 50% to + 100%, the estimated NPV value 0 goes falls between − 1.9 and + 3.7 million EUR (Fig. 7A). This change is critical for the determination of the IRR, especially when a reduction in the amount or price occurs, as a default discount value of 10% is rationally needed while calculating the IRR. In TC, the NPV is even more sensitive, and in the same range, it shows a variation between − 5.7 and + 11.5 million EUR, while the IRR falls between − 15% and 36% (Fig. 7B). The screening and turning of windrows were observed to be the most expensive batch operations in terms of production costs of WC and TC, which affects the economic feasibility, but they play a critical role in WC. Further, the IRR of screening and turning operations in WC cannot be calculated if the cost increases beyond 70% (upper limit) or goes below 10% (lower limit).

Unlike WC and TC, LS is recognized to be less dependent on batch operations, so the cost becomes the most critical parameter, having almost the same influence on the amount and price of the final product. Any changes in these three parameters (i.e., amount of the final product, price of the target product, and CaO) negatively impact the overall cost, thus making IRR unfeasible. However, when changing the final product amount and price in the same range between − 50% and + 100%, the NPV of LS varies between − 2.2 and + 4.5 million EUR (Fig. 7C). The sensitivity analysis based on the IRR of biofertilizer production from the case WWTP-derived biosolids using WC, TC, and LT is shown in Fig. 8A, B and C, respectively. Notwithstanding, if the price for raw dewatered biosolids is taken into account to evaluate the target product price, then it creates an even smaller impact on the sensitivity for all approaches, and almost does not show any influence on the determination of corresponding NPV and IRR. The analysis showed that the total CAPEX seemed to be less sensitive for WC and LS, although in both cases, a small initial investment is needed; however, in the case of TC, it varied from + 3.1 to − 6.1 million EUR, with − 50% to + 100% cost changes.

While analyzing the technological options, it is obvious that the amount and selling price of the produced

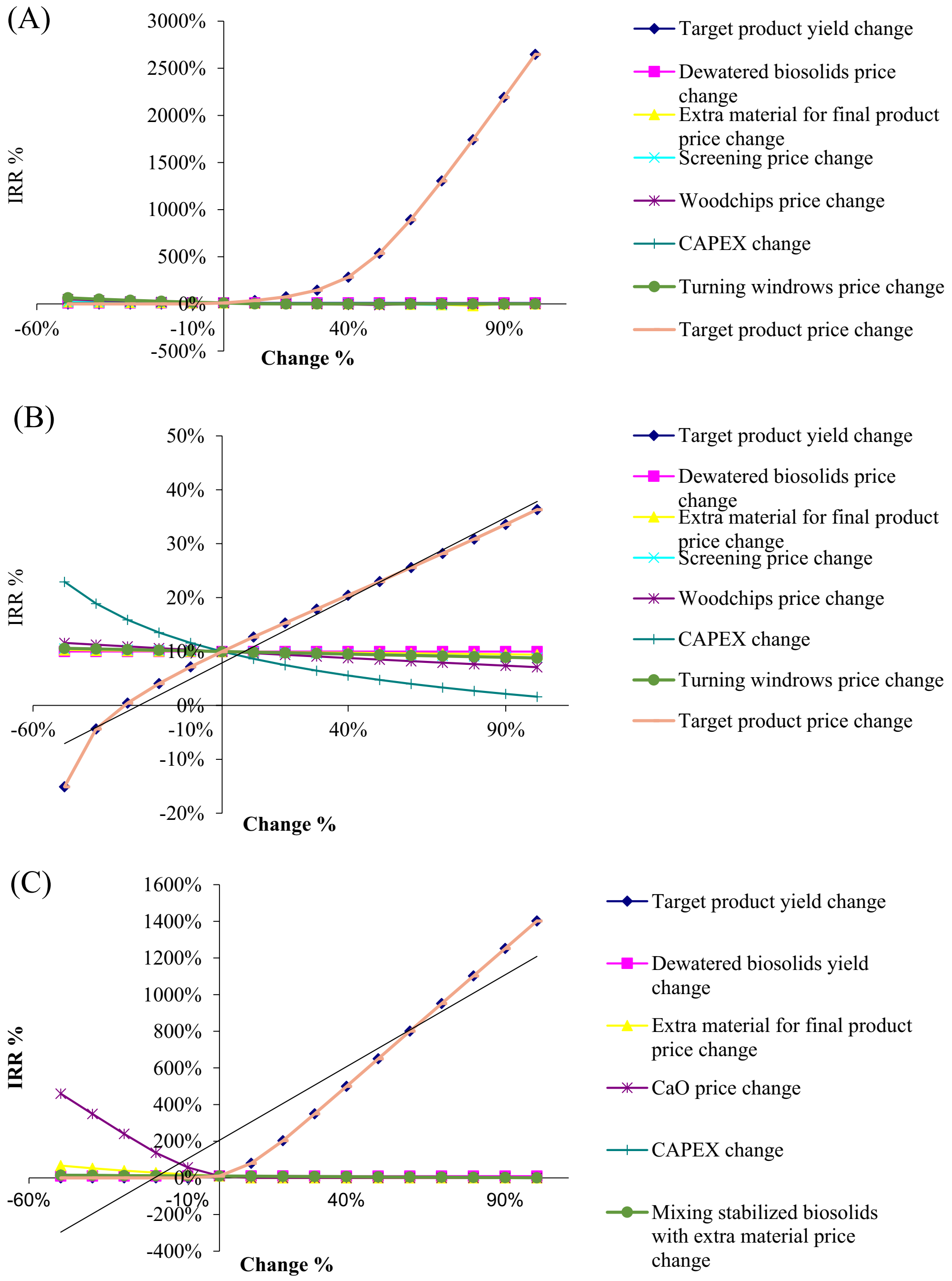

**Fig. 8** Sensitivity analysis based on IRR of biofertilizer production from wastewater biosolids using WC (**A**), TC (**B**), and LS (**C**) technological options

biofertilizer are paramount, as they decide the economic feasibility; thus, precise information on sludge-based biofertilizer production and market analysis are needed for its future applications. In practice, the amount of biofertilizer produced directly depends on the moisture content and dry solid content of the stabilized biosolids since these parameters influence the volume and mass of the final product. In our observation, substituting the targeted product biofertilizer marketing to topsoil for landscaping purposes may be challenging since the existing pricing of topsoil remains below that of our proposed threshold price (9 EUR/m$^3$) of the produced biofertilizer. However, such challenges can be overcome if biofertilizers produced from WWTP-derived biosolids can be popularized by diversifying their applications, for instance, use in horticulture, gardening, and other agricultural purposes as soil fertilizing agents and as an alternative to chemical fertilizer. Such practices may offer more environmental and economic sustainability since the method is eco-friendly and offers sustainable management of biosolids and other pollutants, as well as reduces possible hazardous impacts from chemical fertilizers and saves money on their import.

Several studies have proven that nutrient recovery schemes from WWTPs sludges seem able to generate a positive cash flow. For instance, a feasibility study on phosphorus recovery using a reactor and an anaerobic tank at five WWTPs in Säo Paulo, Brazil, revealed that the revenues exceeded the OPEX (Operational Expenses) at all facilities, indicating the economic viability of this nutrient recovery scheme at a commercial level in that region [7]. Nättorp et al. [39] assessed the cost of three different processes (i.e., precipitation, sludge leaching, dry sludge/ash treatment) for phosphorus recovery from WWTPs in Germany from an investor's perspective. They found that at least one process (precipitation) is profitable, another one (ash treatment) is on the verge of becoming profitable, and the third one (sludge leaching) is on a marginal level or even lower than the market price of phosphorus derived from triple superphosphate. Meanwhile, a study from the Netherlands showed that the sale price of wastewater-based struvite fertilizer at 55 EUR/ton could be viable for commercial-scale operation [40]. A recent study from Egypt showed that the processing of WWTP-derived sludges using WC for biofertilizer production seems to be a sustainable solution [12]. Moreover, the applicability and the economic benefits depend on the orientation of the specific method, the quality and quantity of biosolids, and the operational efficiencies applied at specific WWTPs, as well as on the national regulations and standards [19, 41].

Notwithstanding, our study clearly delineated that biofertilizer production from the observed WWTP-derived biosolids through WC and LS can provide positive cash flow, with a rather small initial investment. Thus, a concurrent detailed assessment of CAPEX is needed to justify the use of WWTP-derived biosolids for biofertilizer production at a commercial level. Interacting with the local stakeholder and WWTP operators, it was known that, in the local markets, the price of fertile soil/vermicompost (a material similar to our target product, that is, biofertilizer) is varied between 50 and 70 EUR/m$^3$. Hence, the threshold price of WWTP-derived biofertilizer (19 EUR/m$^3$) determined in the case of WC and LS seems to be affordable for local consumers in Russia. Our study envisaged that if the prices of the target product, biofertilizer, reach 70 EUR/m3, it could further provide a more positive economic return for the utilization of WWTP-derived biosolids on a commercial scale. Thus, interventions in governmental policy supporting market access of biofertilizer, its popularization, and integration of these materials into the existing distribution channel for its application as fertilizer are, therefore, important.

## Quality evaluation of WWTP-derived sludge

Table 4 represents the key characteristics of treated wastewater sludge in the case 1 and case 2 WWTPs and other WWTPs in Moscow, St. Petersburg, and Sochi. The heavy metals concentrations in our case WWTPs sludges are lower than the treated wastewater sludges in other WWTPs in Moscow, St. Petersburg, and Sochi. In addition, the concentrations of primary nutrients such as N, TP, and K are higher in our case WWTPs-derived sludges indicating better quality of the sludges. However, Table 5 shows the permissible heavy metals and As (arsenic) concentrations in sewage sludges (biosolids) in Russia [9], USA [13], and EU MS (Member States) [42]. It revealed that the heavy metals concentrations in our case WWTPs-derived sludges are considerably lower than that of the allowable limits (see Table 5) indicating the sludges are good enough to meet the set standards.

Nevertheless, pH of treated sludge is generally considered as a mature parameter [43]. A pH value of > 5 seems to be a satisfactory level of a sludge-derived biofertilizer for accelerating plant growth [44]. Furthermore, the presence of N (%DM) is considered one of the main parameters in assessing sewage sludge-derived biofertilizers [44]. Bożym and Siemiatkowski [45] found that the value of N, K, and TOC in a 2-week treated sewage sludge was 3.1, 0.4, and 33%DM, respectively. They also found that the typical concentrations of Pb, Cd, Ni, Cr, Zn Co, and Mn were 28, 0.89, 12, 24, 585, 5.7, and 51 mg/kg, respectively, indicating most of the heavy metal concentrations (except the concentrations of Cd and Mn) in our case WWTPs-derived sludge are lower than that their findings [45]. The explanation of a higher concentrations of Cd and Mn in our case-1-WWTP-derived sludges was probably cause of discharge of the heavy metallic substances into the sewage system that partly explained

**Table 4** Key characteristics of treated wastewater sludge in the case 1 and case 2 WWTPs and other WWTPs in Moscow, St. Petersburg, and Sochi (concentrations in mg/kg)

| Element | Case 1-WWTP | Case 2-WWTP | *Moscow | *St. Petersburg | *Sochi |
|---|---|---|---|---|---|
| pH | 6,4 | 6.2 | 7,00 | 7,1 | 7,2 |
| MC (%) | 76,2 | 77.3 | 70 | 75 | 89 |
| N (% DM) | 4,3 | 4.8 | 1,5 | 4,3 | 3,4 |
| TOC (% DM) | 32,3 | 32.3 | 0 | 0 | 0 |
| TP | 6,9 | 11.8 | 4,5 | 2,4 | 1,9 |
| K | 3,4 | 3.4 | 0,7 | 0,4 | 0,3 |
| Pb | 13 | < 0.001 | 30–50 | 52 | 70 |
| Cd | 5 | 0.001 | 9–12 | 26 | 6 |
| Ni | none | 0 | 50–80 | 130 | 100 |
| Cr | 12 | 0.03 | 360–600 | 260 | 0 |
| Zn | 270 | 0.41 | 600–1100 | 960 | 1669 |
| Cu | 180 | 0.17 | 400–600 | 445 | 406 |
| Hg | 0 | < 0.001 | 0 | 0 | 0 |
| Mn | 200 | 0.5 | 520 | 825 | 760 |

Source: *[9]

**Table 5** Permissible heavy metals and arsenic concentrations in sewage sludges (biosolids) in Russia, USA, and EU MS (concentrations in mg/kg)

| Element | [a]Russia | | [b]USA | | [c]EU MS |
|---|---|---|---|---|---|
| | Group I | Group II | Group I | Group II | |
| Pb | 250 | 500 | 300 | 840 | 750–1200 |
| Cd | 15 | 30 | 39 | 85 | 20–40 |
| Ni | 200 | 400 | 420 | 420 | 300–400 |
| Cr | 500 | 1000 | 1200 | 3000 | ca.500 |
| Zn | 1750 | 3500 | 2800 | 7500 | 2500–4000 |
| Cu | 750 | 1500 | 1500 | 4300 | 1000–1750 |
| Hg | 7,5 | 15 | 17 | 57 | 16–25 |
| As | 10 | 20 | 41 | 75 | ca.25 |

Sources: [a] [9], [b][13], [c][42]

the phenomenon; however, the level of the concentrations is still lower than the allowable ones (see Table 5). The key characteristics of our case WWTPs-derived sludges poses a better quality than that of the sludges of other WWTPs in Moscow, St. Petersburg, and Sochi—eventually, indicating the suitability of our case WWTPs-derived sludge for biofertilizer production.

In Russia, the development of a WWTP-derived biofertilizer business plant needs to abide by the existing environmental laws, standards, and regulations [46]. The utmost state legislative and normative documents are 'SanPiN 2.1.7.573–96 (Hygienic requirements to wastewater and sewage sludge use for land irrigation and fertilizer)', 'Typical technological protocol for using of wastewater sludge as an organic fertilizer—2000' that approved by the Russian Ministry of Agriculture, and 'GOST R 17.4.3.07–2001 (Requirements to wastewater sludge for its application as a fertilizer)'. These documents provide the guidance on performance standards of heavy metals concentrations in sludges or its by-products for soil applications (Kalyuzhnyi 2007). These are known as ceiling concentrations that cannot be exceeded in biosolids products including composting.

However, our study did not investigate on the dynamics of compositional changes during the different composting process, the values of nutrients of stabilization of sludge, respiration activity ($AT_4$), the cumulative amount of easily bioavailable nitrogen (EBN), coli-index and other relevant parameters for overall quality assessment of the sludges. An earlier study showed that the properties and heavy metal concentrations of raw sewage sludge change during composting processes and the degree of their levels differs in the final product [45]. Thus, a detailed further investigation of these aspects is required prior to commercial utilization of the resource for biofertilizer production through the selective composting technological options.

## Conclusion

This study demonstrated the techno-economic evaluation of WWTP-derived biosolids for biofertilizer production using WC, TC, and LS in the northwestern region of the Russian Federation. It highlights the suitable options for recycling biosolids to produce biofertilizers, in terms of economic returns and investment planning at an enterprise level in Russia as a case. Based on the yearly amount of discharged biosolids of 22,000 $m^3$, the volume of biofertilizer production can be increased by 1.02 to 1.59 times if they are processed using the proposed technological options. Considering the CAPEX, IRR, and DPP, WC comes across as the most efficient technological option, followed by LS.

Both WC and LS seem to be attractive for investment in the Russian context if the selling price of WWTP-derived biofertilizer is capped at 19 EUR/m$^3$. On the other hand, TC involves a greater CAPEX, higher DPP, and rather an intensive operation procedure; hence, its implementation is not encouraged. Moreover, the study found that the key characteristics of the WWTPs-derived biosolids are good enough to meet the national and international standards to produce biofertilizer for land applications. However, the main concern regarding marketing WWTP-derived biofertilizers is that their base price needs to compete with the existing materials (e.g., topsoil, fertile soils). Interventions such as popularization and diversification of the usages of biofertilizers for agricultural purposes, research on efficient biosolid recycling technologies and their quality assurance, governmental policy support on production and marketing of WWTP-derived biofertilizers are, therefore, imperative. However, this study does not present a detailed analysis of the nature of nutrients of the raw sewage sludge and biosolids, the dynamic changes during composting, and the composition of the target product, that is, biofertilizers. Thus, further study is needed to evaluate the overall development of sustainable management of WWTP-derived biosolids and the commercialization of the resources.

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