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Effect of future environmental laws on the WWTP sustainability in Algeria – case study on phosphorus discharges and sewage sludge management

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ABSTRACT

Life cycle assessment (LCA) study was carried out with Gemis software. The aim was to evaluate the effect of future environmental law on phosphorus discharges on the sustainability of one wastewater treatment plants (WWTP) in Algeria. The wastewater treatment generated 6.04 kg CO_2eq/cap y. It consumed 95.9 MJ/cap y of cumulative abiotic energy (CEC_{ab}) and 3.84 kg/cap y of cumulative abiotic mineral (CM_{ab}), allocated respectively to energy and chloride ferric production. For extended system boundaries, two sludge recovery strategies were assessed in comparison to the current law: co-incineration and agricultural spreading. The improvement of phosphorus removal to 80% by chemical precipitation increased the global warming potential of these scenarios respectively, of 0.26 and 0.38 kg of CO_2eq per g of removed phosphorus. These strategies improved the WWTP sustainability, but the new regulation reduced their substitution effect. The co-incineration with cogeneration was the best on the basis of CEC_{ab} while spreading was the best one in terms of CM_{ab}, acidification, and photochemical oxidation impacts. The choice between these two strategies depends also on the (eco) toxicity impacts and the national economic context. Improving the sustainability of urban wastewater systems should take into account the decrease sludge volume and their nutrient content as well as possible updates of current and future regulations.

Keywords: Algeria; Co-incineration; Laws; LCA; Phosphorus; Sludge; Spreading; Sustainability; Wastewater

1. Introduction

Developing countries face constraints to synergize economic development and environmental protection. The land use pressure is only a consequence if we add growth and demographic mobility factors. Algeria is confronted with multiple structural changes that aim to improve the life quality of its citizens, especially that it has a variety of natural resources. About 80% of the population live on the edge of the Mediterranean because of access to work and semi-arid climate. Consequently, the authorities will have to optimally manage fossil resources, the main engine of the country's economy, as well as water resources and the protection of the environment, particularly Algerian coast. The United Nations has set up an action plan for the Mediterranean in order to limit the eutrophication of sensitive areas [1]. Nitrogen and phosphorus are the main causes of eutrophication, which are largely carried by aqueous discharges. If nitrogen is found in abundance in

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the environment, phosphorus is a nonrenewable resource ending up in the aquatic environment. As a result, more dephosphatation and denitrification must be completed at the wastewater treatment plants (WWTP). Algeria, one of the contracting countries of the Barcelona Convention, has not accepted yet and ratified the LBS protocol: protocol for the protection of the Mediterranean Sea against pollution from land-based sources and activities [1]. Almost all the contracting countries ratifying this protocol have harmonized the restriction for total phosphorus to 2 mg/L or 80% catchment for sensitive areas of 10,000–100,000 PE and 1 mg/L or 80% for more than 100,000 PE. The restriction for total nitrogen is 15 mg/L or 70%–80% catchment for sensitive areas of 10,000–100,000 PE and 10 mg/L or 70%–80% for more than 100,000 PE. The current regulations in Algeria are not restrictive for the nitrogen and phosphorus discharges to reduce eutrophication. The last regulation law of 2006 sets the limit of total nitrogen at 30 mg/L and the limit of total phosphorus at 10 mg/L [2]. This regulatory law repealed an old one dating from 1993 limiting the Kjeldahl nitrogen to 40 mg/L and phosphates to 2 mg/L [3]. The change in regulatory laws has always been linked to the change of the governance system. In Algeria, urban WWTP are designed essentially to eliminate carbonic and particulate pollution omitting nitrogen and phosphorus pollutions. The majority of its WWTPs operates by activated sludge process that produces large amounts of sludge. With a policy to reduce eutrophication of sensitive areas, more investments will be necessary at the WWTPs to achieve high denitrification and phosphorus removal efficiency. This change could influence the current WWTP and sewage sludge management strategy. The installed capacity of urban wastewater plants is 6.88 million equivalent inhabitants producing an annual quantity of sludge of 38,690 tons. The final destination of the sludge in Algeria is 60% in landfill, 25% in agriculture, and 15% are stored [4]. The landfill route has been banned completely in developed countries because of increasingly stringent environmental regulations and land availability issues in overly populated cities. In Algeria, there are also questions to ask regarding the use of land for agricultural, urban, or landfill purposes. Consideration should also be given to protect large groundwater reservoirs from the risks of contamination. Sludge disposal complexity in Algeria is studied on the large scale decision basis using life cycle assessment (LCA) [5]. This study answers to the following question: what would be the most feasible, using sludge as fertilizer or incinerating and recovering its energy value? The issues of climate change and natural resources depletion are receiving much attention in urban wastewater treatment planning policies [6,7]. LCA (ISO 14044:2006) is a decision tool that evaluates the sustainability of systems on their whole life cycle (from "cradle" to "grave") by quantifying pollutant transfers and the substitution effects of both strategies on environmental impacts. It permits to choose the best strategies and to detect further improvements [8,9]. According to a case study which concerns the WWTP of Guelma City, it is shown that spreading and co-incineration reduce environmental impacts and represent the best strategies compared to landfill and mono-incineration. The sludge contains nitrogen and phosphorus nutrients that can therefore be used as fertilizer. Nitrogen (N) and phosphorus (P) are essential nutrients for increasing crop yields. The sludge has an energy potential to be converted into a cogeneration system with urban wastes. The lower heating value (LHV) of the semi-dried sludge is 1.921 MJ/kg [5] below that estimated in the literature about 2.3 MJ/kg [10]. When it is co-incinerated with the municipal solid waste, the LHV of the mixture, and the furnace temperature are lowered. It is indicated that the higher the co-incineration ratio is, the LHV of the mixed fuel is lower. It increases also the unburned combustible waste [10]. Both strategies have a substitution effect of environmental impacts which has to be evaluated in relation to regulations amendment. The choice between the two strategies depends on which resource we prefer to substitute, fossils, or ores ones. Energy recovery substitutes fossil fuels consumption, in particular natural gas, but increases the share of minerals required for the reduction of exhaust gases. The spreading replaces the ores used in synthetic fertilizer manufacturing.

The aim of this work was to study the effect of the phosphorus removal improvement to 80% with simultaneous chemical precipitation (structural modification) on the impacts of the WWTP of Guelma City. This additional treatment increases the amounts of sludge to be disposed in co-incineration or spreading. It allows up the removal of P nutrients that end up in sludge and therefore improve the potential fertilizing. This study was made by the LCA, and it consists of four steps, starting with the definition of the objective and the scope of the study, life cycle inventory, evaluation of the life cycle impact, and interpretation [8,9]. It was partially based on *in-situ* and data report of the regional National Sanitation Office (ONA) for the period between 2013 and 2015. It was conducted on the basis of four criteria: Cumulative abiotic resources use for Fossil (CEC_{ab} in MJ) and for mineral (CM_{ab} in kg), global warming potential (GWP in kg CO_2eq) for a period of 100 y, acidification potential (in kg SO_2eq), and tropospheric ozone precursor potential (TOPP in kg TOPPeq). Gemis software version 4.9 was used to complement data, to model other processes, and to calculate environmental impacts [11].

2. Methods

2.1. LCA system boundaries

Electricity generation was modeled according to the Algerian energy mix of 2015 [12] in which were integrated data of natural gas extraction, its transport, and conversion [5]. The calculation result for 1 kWh production is 8.51 MJ of CEC_{ab}, 496 g CO_2eq, 1.58 g SO_2eq, and 2.9 g TOPPeq [5]. This calculation is made with Gemis according to the Ministry of Energy's publication in 2017 [12] and World Bank statistics in 2015 [13]. Transportation and manufacturing stages were excluded from all processes except for materials used in renewable electricity and chemical precipitant production. The direct pollution load of the sludge elimination module was considered except for the spreading. N_2O and CO_2 emissions from activated sludge were not counted as well as those related to sludge during storage and spreading. The substitution effect was considered for electricity production and heat of cogeneration as well as for nitrogen (N) and phosphorus (P) synthetic fertilizers of sludge nutrient recycling in spreading. The extended fields of study took into account the direct impacts of WWTP system. The analysis was composed of two parts: the current regulations (reference scenario) and the new regulations (new scenario) where each part of the landfill was used as a reference scenario. The chosen functional unit was the treatment of one m^3 of wastewater for 1 y [14] and the allocation was made on physical treatment (Fig. 1). The technologies used from databases of Gemis were adapted to the Algerian electricity mix and for a period technology between the years 2000 and 2010. The data related to the Guelma WWTP operation represent the average obtained during the period of 2013 and 2015, considered to have a good quality. The eco-design of sludge management strategies is influenced by the electric mix [15] so an analysis of the system with a Horizon 2030–2040 energy mix has been integrated. The goal was to compare the two strategies and to identify improvements through contribution analysis. The Algerian energy mix by 2030–2040 is modeled by the incorporation of 40% of photovoltaic energy, according to the processes available and planned by Gemis by 2030 [5]. The impacts of 1 kWh are reduced by 41% with the exception CM_{ab} which increases by 5% due to the corresponding investments. The normalization and weighting were not considered in the impact evaluation step as well as the impacts of eutrophication, toxicity, and ecotoxicity.

2.2. System modeling and inventory analysis

2.2.1. WWTP description

The WWTP of Guelma city, connected to a unitary sanitation, has been operational since 2008 and managed by the National Sanitation Office (ONA). It is a conventional activated sludge system that has received in the period between 2013 and 2015 the load of 117,000 inhabitant equivalents. The yearly load of inhabitant equivalent considered was 11.32 kg of TSS, 11.39 kg of BOD_5, 20.81 kg of COD, 2.85 kg of total nitrogen, and 0.98 kg of total phosphorus. The discharge pollutants into the sewage systems of developing countries exceed 1 kg/cap y of phosphorus and 5 kg/cap y of nitrogen [16]. The wastewater is moderate according to site-specific data and to wastewater characteristics [17]. An analysis of the parameters was performed to calculate WWTP efficiency and nutrient content in the sludge [5]. By introducing a new release limit for phosphorus, monitoring of phosphorus and parameters contributing to eutrophication would often be carried out. The operation takes place in three essential steps: mechanical pre-treatment, primary settling, and secondary treatment (Fig. 1) The impacts of solid wastes and sand generated from pre-treatment of WWTP were excluded from this study. The produced sludge is thickened, stabilized, and loaded on a drying bed. The sludge produced was 20.31 kg DM/cap y of 43%. The low-load operation allows the removal of nitrogen and phosphorus. The WWTP allows a reduction of pollution below the limit values set by the current Algerian regulations [2]. The elimination of nitrates is ensured partially and it affects biological dephosphatation in anaerobic zones obtained by alternating aeration. The extended aeration activated sludge ensures an elimination of total phosphorus of 52% through the biological dephosphatation process. The chemical dephosphatation by ferric chloride (14%) was theoretically introduced to push this yield up to 80%. The inventory analysis of ferric chloride was taken from literature with the assumption of old process [18]. The amount of added ferric chloride and the new sludge volume were calculated on the basis of the current efficiency of the WWTP and literature [17,19]. Precipitation was assumed to be simultaneous during secondary treatment considering one mole of Fe reacting with 1 mol of precipitated phosphorus and with a biochemical oxygen demand/total phosphorous (BOD/TP) mass ratio of 11.55 [17]. The new sludge volume was estimated based on the reduction rate of the thickener and the drying bed at the Guelma WWTP and the excess sludge production of the secondary sludge due to chemical precipitation, which was calculated using the model published by [19]. The same percentage of dry matter in the sludge of the reference scenario was considered. The observed yield of organic sludge production (Y_{obs}) used in the calculation was of 0.63 g VSS/g COD consumed. This parameter was estimated by considering the solids retention time (θ_b) of 2.5 d for P-removal reaction time in simultaneous precipitation. The kinetic coefficients used were 0.71 g VSS/g COD consumed for the biomass yield (Y), and of 0.05 d^{-1} for the decay coefficient (k_d). All the other coefficients in the model were maintained. The sludge volume was therefore increased by 18.45% and the concentration of total phosphorus in the dried sludge had become 3.42% instead of 2.62% in the reference scenario.

2.2.2. Modeling of sludge co-incineration, spreading, and landfilling

For sludge co-incineration, we used the biogenic residential waste incineration module of Gemis that includes the cogeneration with a steam turbine, exhaust gas reduction, and $DeNO_x$ operation. The control systems reduce air emission below regulated limits of the European Union. The elimination of ashes in landfill was introduced in this module. The composition of a biogenic residential waste was considered relatively close to that of sludge except for nutrients. Therefore, the incinerator model of the biogenic wastes set for the exhaust gases calculation was assumed to be valid to the sludge. The inlet composition was adapted to the sludge one, the primary fuel source in this module. The power set by Gemis is 10 MW and the fuel supply is 4.84 kWh per 1 kWh of the produced electricity, the output product of the module. The by-products were allocated, therefore, wholly to the total energy content of the produced sludge. The Gemis software does not have a module for the incineration and co-incineration of sewage sludge and the used module does not take into account the heavy metals content of the supplied wastes. Furthermore, the concentrations released from the ash elimination module were not closed to that contained in the considered sludge. This LCA study was conducted on the basis of five impacts and the effects of the heavy metals were excluded. We considered the substitution of electricity produced by the energy mix of Algeria. The modeling of the substitution effect of the heat use was made considering central residential heating of Gemis databases with Algerian natural gas. The recovered thermal heat from the steam turbine was estimated at 30% of the produced useful energy estimated at 20% of the sludge's energy content. The heating value of the sludge was calculated with the Gemis model based on sludge composition like nitrogen, water, ash, and carbon contents but not influenced by phosphorus. The lower and higher calorific value calculated for the semi-dried sludge with a nitrogen content of 4% DM were, respectively, 1.921 and 3.566 MJ/kg. Incineration of sludge requires the use of secondary fuel if the moisture is too high, assumed not necessary in the present contribution. The recovered energy into electricity and heat forms were calculated for current sludge with a nitrogen content of 4% DM, respectively, of 18.15 and 5.44 MJ/cap y which remained far below the values found in the literature [20,21]. The key parameter regarding the energetic use of sewage sludge is the volatile matter (VM). Dry matter (DM) contributes to the fuel requirements and exhaust gas production at the incineration stage [21] but also to the substituted energy. Therefore, the heating value of sludge and the substituted energy were increased for the new regulation of 18.45% for the same content of nitrogen.

The amount of substituted synthetic fertilizer was estimated by considering average that 50% of nutrients contained in the sludge are available for the crops [16]. It is assumed that 50% of the nitrogen is lost as ammonia and nitrogen [18] and the phosphorus uptake is similar to nitrogen one [16]. The restrictive standards for the application of sludge as fertilizer limit the quantity of sludge to be treated per hectare during crop rotation [22] in particular because of the risk of phosphorus, which inhibits the bioaccumulation of certain trace elements and produces leachate in the agricultural soils. The heavy metal contents in the sludge from the Guelma WWTP were lower than those fixed by the standards of the European Union, noting that there are still no regulatory laws in Algeria. The contents of the heavy metals present in the sludge of Guelma WWTP were given in mg/kg DM as follows: cadmium (7 ± 1.4), chromium (31 ± 13.42), copper (122 ± 17.58), nickel (37 ± 2.51), zinc (533 ± 128.71), Cr + Cu + Ni + Zn (726 ± 138.6), lead (14.5 ± 7.78), and mercury ($5 \times 10^{-3} \pm 0.7 \times 10^{-3}$). These concentrations were below the restrictions in terms of heavy metals set by the Algerian Standard NA 17671 [23]. This standard remains anyway above of these fixed in the developed countries and they then could be inevitably revised in the future. The conditions of the sludge implementation also should be reviewed by considering the risks of phosphorus and organic micropollutants. The regulatory laws would also be concerned with the atmospheric discharges of mono-incinerators and urban waste co-incinerators not yet set. We adapted the modules of synthetic nitrogen and phosphorus fertilizers of Gemis from the extraction of raw materials to the output of production processes by using the Algerian energy mix. The quantity of N and P synthetic fertilizers avoided by the current sludge was 0.417 and 0.265 kg P/cap y. The amount of phosphorus in sewage sludge is often closer to half the nitrogen content [22]. Based on dry matter, the content of total nitrogen, and total phosphorus in the current sludge was respectively 4% and 2.62% in the same order of magnitude of the mean values found in the literature respectively 4% ± 0.2% and 2.47% ± 0.53% [5]. After chemical dephosphation the content became 3.45% for total nitrogen and 3.7% (0.411 kg P/cap y) for total phosphorus close to the values obtained in the literature [16,24]. The fertilizing potential was thereby increased by 28.51%.

We adopted the model of [14,26] for landfilling of sludge of 26.6% dried matter and 31% of volatile matter (French context). The model considers direct gaseous emissions, production, treatment, and direct emissions of leachate and ash production. The recovery of gaseous emissions from landfill was not considered as landfills in Algeria are mostly uncontrolled and there is still no policy to manage the leachate. So the biogas formed (105 kg/t DM) is oxidized in the soil and emitted into the air without being burned. The French regulation is used to estimate the composition of biogas, volume, and leachate concentration. The model takes into account the annual rainfall conditions, the depth of discharge, and a long duration of the operation.

The energy consumption of the reference WWTP was calculated as 34.56 MJ/cap y (0.63 MJ/m^3). The treatment of wastewater consumed 81.71 MJ/cap y (1.49 MJ/m^3) of CEC_{ab} and 0.011 kg/cap y (0.19 g/m^3) of CM_{ab}. The WWTP generated 4.76 kg/cap y (87 g/m^3) of CO_2eq, 15.2g/cap y (0.28 g/m^3) of SO_2eq and 27.9 g/cap y (0.51 g/m^3) of TOPPeq. The reducing of PT emissions by up to 80% increased WWTP consumption by 17.4% for CEC_{ab} and 3.83 kg/cap y of CM_{ab} due to the ferric chloride. It also increased CO_2eq by 27%, SO_2eq by 81.34%, and TOPPeq by 7.73%, mainly caused by $FeCl_3$ production. This was the same increase recorded for direct impacts, including WWTP and landfill disposal, except the impact of global warming where it was 20%. On a system boundary, including WWTP and sludge removal, improving the phosphate removal efficiency increased the direct impacts. If the sludge is co-incinerated, the increase in total direct impact was of the same order of magnitude for CM_{ab} as in WWTP + landfill scenario. It was lower for CEC_{ab} (14%) and acidification impact (16.38%) and higher for GWP impact (25.47%), while that the TOPP impact decreased by 26%.

3. Results

3.1. Comparison of the potential impacts with current regulation (reference scenario)

The direct impacts and substitution effects (the net impacts) in the regulation in force were compared in Fig. 2. Compared to the landfill scenario, the co-incineration scenario reduced the GWP impact by 93.35% (30.73 kg CO_2eq/cap y), the CEC_{ab} by 58.95% (49.35 MJ/cap y), the TOPP impact by 33.86% (14.29 g TOPPeq/cap y), and increased slightly the acidification impact by 5%. The increase was higher for the CM_{ab} by 337.34% (0.037 kg/cap y), mainly for exhaust gas reduction and $DeNO_x$ operation.

The sludge spreading scenario reduced the GWP impact within the same magnitude of the co-incineration scenario by 95.14% (31.31 kg CO_2eq/cap y) but it was lower for the CEC_{ab} by 31.68% (26.53 MJ/cap y). However, the improvement was higher for the TOPP impact by 62.66% (26.45 g TOPPeq/cap y) and the acidification impact by 112% (17.42 g SO_2eq/cap y). The co-incineration scenario outweighed the spreading scenario for the CEC_{ab} impact due to the substitution effect of cogeneration (Fig. 2). The

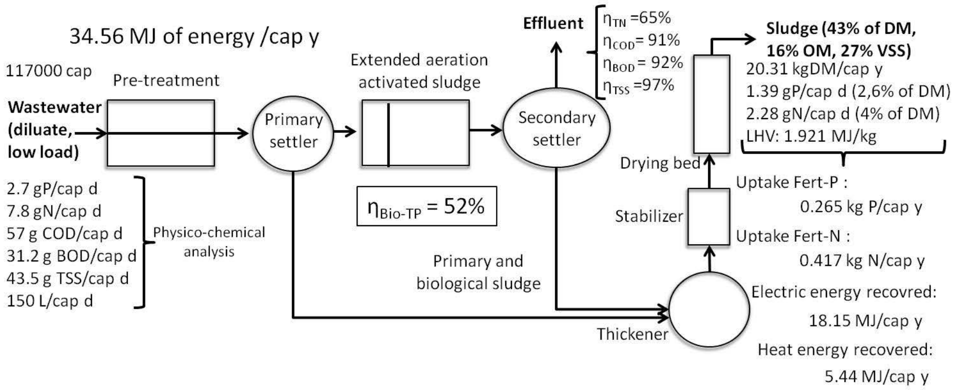

Fig. 1. Current WWTP (reference WWTP).

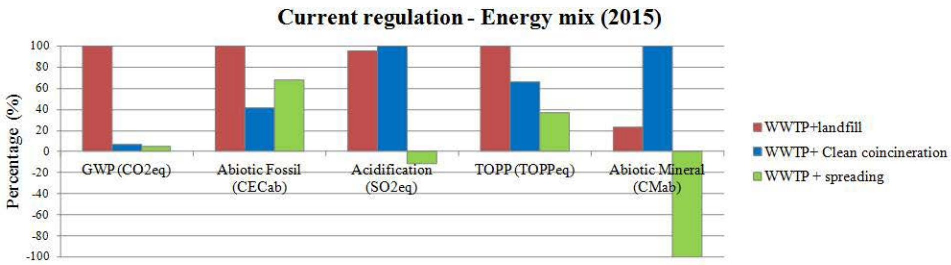

Fig. 2. Comparison of the net potential impacts of scenarios in the current regulation.

negative value in the histogram (Fig. 2) represented the CM_{ab} substituted by the spreading of sludge estimated at 1.37 kg/cap y. The $DeNO_x$ process was responsible for increasing the CM_{ab} impact in order to trim down the regional impacts of acidification and TOPP which had remained greater than in the spreading scenario. The impacts of CM_{ab} in the co-incineration scenario would be susceptible to increase with more restrictions on atmospheric releases.

3.2. Comparison of the potential impacts with the new regulation (new scenario)

The direct impacts and substitution effects (the net impacts) in the new regulation were compared in Fig. 3. The improvement of phosphorus removal to 80% in the WWTP increased all net impacts of the reference scenario with the current regulation. It increased the GWP impact of spreading scenario by 69.2% and of co-incineration scenario by 34.9%, and respectively, by 20.2% and 16% for the CEC_{ab} impact. The acidification and TOPP regional impacts of the co-incineration scenario remained greater than in the spreading scenario, despite the net impacts of the latter being increased. As shown in Fig. 4, spreading and co-incineration scenarios had the same order of magnitude of the direct impacts. It should be noted that the direct impacts of the spreading have been zeroed out to give more benefits to this operation. The energy value of the sludge has been increased with the new regulations due to the increase in dry matter which would be absolutely responsible for the combustion products of the incinerator. The substituted effect of spreading sludge has lost interest due to the use of ferric chloride. The increase in the net impacts was of the same magnitude for the TOPP category in both scenarios (Fig. 3). The increase in CM_{ab} consumption was much higher for co-incineration scenario and agricultural spreading, respectively, of 3.80 and 3.19 kg/cap y, chiefly because of the $FeCl_3$ use (Fig. 5).

The contribution of the exhaust gas treatment and $DeNO_x$ operation of the co-incineration scenario to the CM_{ab} consumption impact became very negligible in comparison with the reference scenario (Fig. 5). The LCA showed that the sludge landfill scenario had always the highest value in all impact categories (Fig. 3). The sludge used in agricultural remained the best choice for phosphorus recycling in the value chain based on the CM_{ab} consumption and the impacts of acidification and TOPP. The co-incineration, on the other hand, provided an economic interest based on the CEC_{ab} consumption and remained competitive with respect to the GWP impact. Table 1 shows the increase in the net impacts, including direct and substitution effect, per g of phosphorus removed by chemical precipitation (g $P_{Chemical}$).

The difficulty in developing countries is the availability of chemicals and the proximity of treatment plants. In sensitivity analysis, the impacts of ferric chloride transport from a distance of 50 km were of the same order of magnitude as the direct impacts of the co-incineration process. Decision-makers steer the choice between the sludge mono-incineration at WWTP and the co-incineration with urban waste compared to the impacts the sludge transport and the chemicals used in the control systems of exhaust gases. Auxiliary fuel is often used in mono-incineration and the energy recovered is less attractive than in

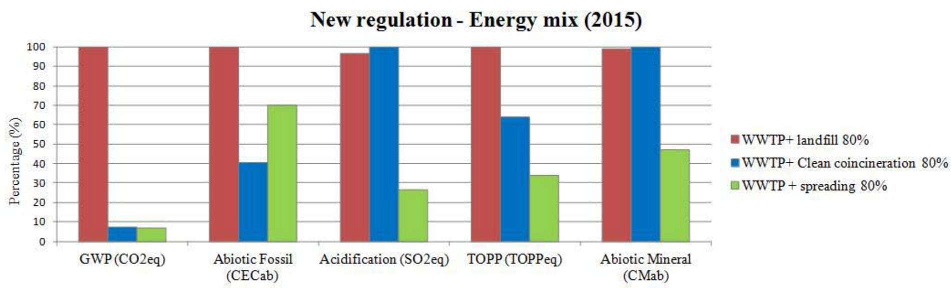

Fig. 3. Comparison of the net potential impacts of scenarios after regulation adaptation.

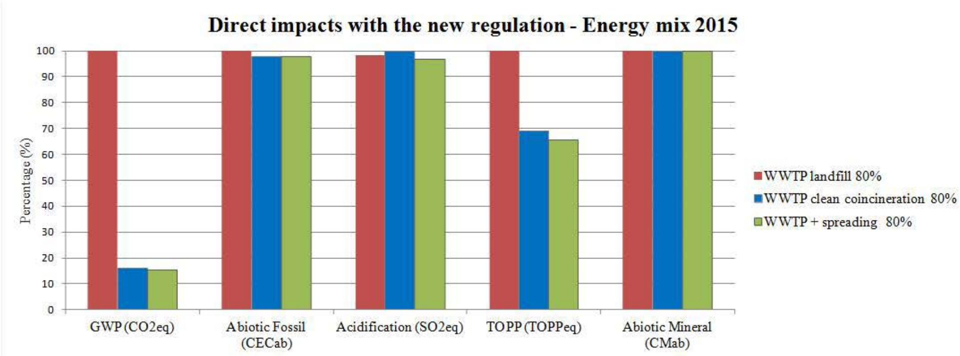

Fig. 4. Comparison of the direct potential impacts of scenarios after regulation adaptation.

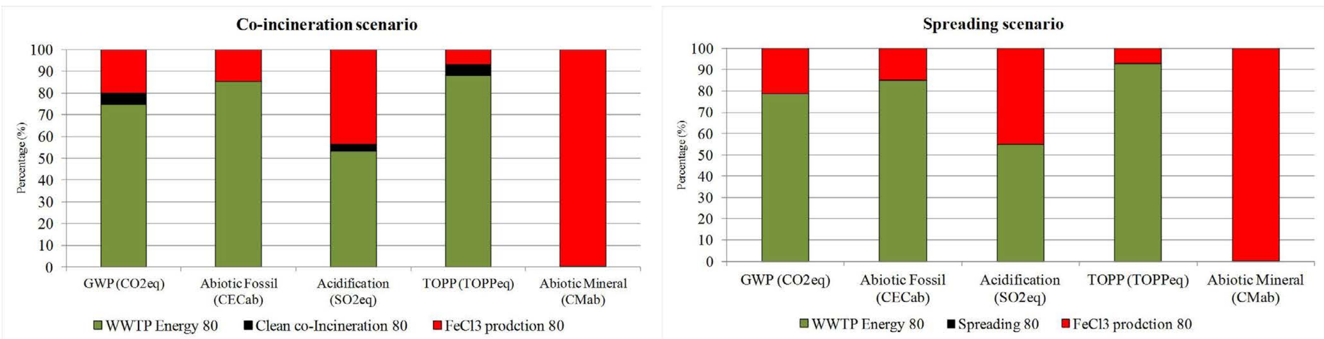

Fig. 5. Processes contribution in the direct impacts of the co-incineration and spreading scenarios.

Table 1
Increase of the total impacts of scenarios including direct and substitution effects per g of removed $P_{Chemical}$

	GWP (kg CO_2eq)	Abiotic Fossil (MJ CEC_{ab})	Acidification (g SO_2eq)	TOPP (g TOPPeq)	Abiotic Mineral (kg CM_{ab})
WWTP + landfill	2.26	4.93	4.24	1.27	1.31
WWTP + Clean co-incineration	0.26	1.89	4.30	0.74	1.31
WWTP + spreading	0.38	3.96	3.25	0.04	1.09

co-incineration [10]. It has been shown that the co-incineration and spreading scenarios remained the best choices, for a sludge transport distance of 25 km (Fig. 6). By comparing the results shown in Figs. 3 and 7, CEC_{ab} and CM_{ab} were the two impacts that influenced the choice between the recovery of sludge in co-generation or spreading. In the co-generation and spreading scenarios, the contribution of the sludge transport in the direct impacts (except for mineral ores) was greater than that of the ferric chloride transport and the exhaust gases from co-incineration (except for acidification and TOPP). It was of the same order of magnitude as the manufacture of ferric chloride and both would constitute the improvement objective (Fig. 8). The activated sludge wastewater treatment systems produce large amounts of sludge to be disposed, which results in a significant contribution to the acidification impact due to the transport [25]. Without taking into account the substitution effect, the mono-incineration is found better than landfill for the resource consumption and photochemical oxidation (TOPPeq) impacts, while the spreading seems to be the best for the GWP and acidification (SO_2eq) impacts [26].

The energy consumption was the first contributor of all direct impacts, while the consumption of abiotic minerals was assigned to the manufacture of ferric chloride. With a future scenario integrating 40% photovoltaic technology in the energy mix, the contribution of sludge transport, and $FeCl_3$ production would increase in the spreading scenario (+45%). In the co-incineration scenario, the contribution of these last two processes was increased only in the GWP, and CEC_{ab} impacts (+46%). Their contributions were reduced, however, in the regional impacts of acidification and photochemical pollution (–10%). The 2040 energy mix made it possible to reduce all the net impacts of atmospheric emissions of spreading scenario by the same order of magnitude (–75%). The decrease was higher than co-incineration scenario (–16%). The reduction in cumulative energy consumption was of the same order of magnitude for the two scenarios with respectively –48% and –32%. The variation in the cumulative consumption of minerals due to investment in solar energy was not at all significant. The spreading scenario, therefore, outperformed the co-incineration scenario in terms of regional impacts of acidification and photochemical pollution while the two scenarios have the same order of magnitude of the global warming potential impact (Fig. 9). With a view to the energy mix by 2040, co-incineration is favorable for saving fossil resources, especially natural gas, the spreading for minerals recovery, especially phosphates.

3.3. Impacts substitution modified by the new regulation

The requirement of effluent quality improved the energy recovery of the sludge of 18.45% and the fertilizing potential of 28.5%. Therefore, the impacts substitution was improved by 18.33% and 5.45% for the GWP impact, relatively, for the co-incineration and spreading scenarios. The improvement was in the same order of magnitude of the other impacts of the energy recovery scenario (18%). However, the substitution effect of spreading scenario was improved by 10.7% for the CEC_{ab}, 16.82% for the acidification and TOPP impacts and 47.8% for the CM_{ab}.

4. Discussion

The LCA results showed that the reduction of eutrophication contributed to the increase of global and regional impacts. The impacts resulting from WWTP modification were different according to the system boundaries that include sludge elimination strategy. The application of the new regulation had allowed the improvement of the fertilizing potential and the sludge energy value. On the other hand, the sludge's volumes were increased, which was

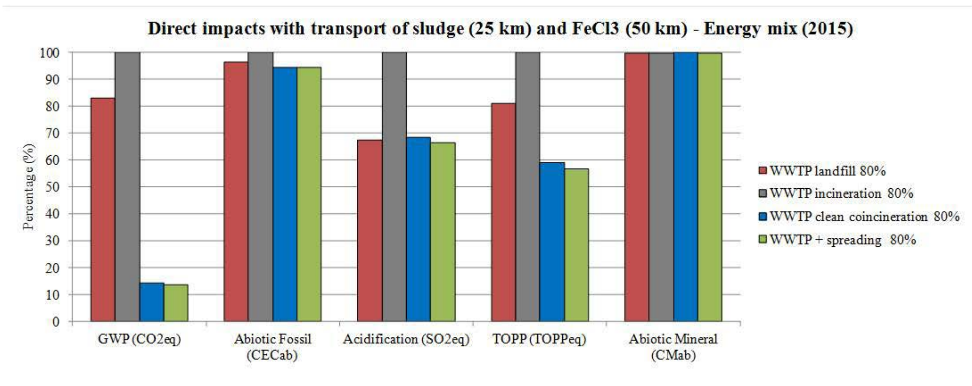

Fig. 6. Comparison of the direct potential impacts of scenarios taking into account transport.

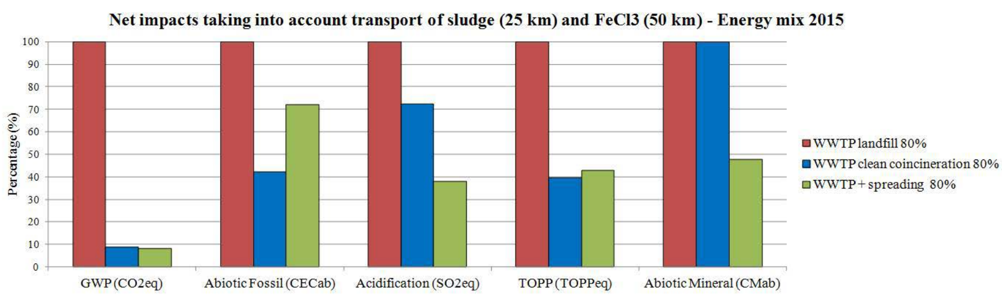

Fig. 7. Comparison of the net potential impacts of scenarios taking into account transport.

being reflected in the regional impacts due to transport and exhaust gases, thus increasing the consumption of ores in the $DeNO_x$ process. The energy recovery of sludge must be accompanied by an exhaust gas control strategy. With the new amendment, the increase of GWP of the exhaust reduction and $DeNO_x$ operation was 3.75% over the current regulation scenario. The increase in other impacts was by the same growth factor in the sludge volume. It should be noted that gas capture process reduced the impact of acidification of 74% and the impact of photochemical pollution by 37%, but it increased the impact of global warming by 215% without precipitation of phosphorus and 176% with the new regulation. However, the required share of minerals for the reduction of exhaust gases and $DeNO_x$ operation was still insignificant with the new amendment in comparison to the total consumption. In the reference scenario, the amount of sludge burned in incinerator plant was 9.07 kg per 1 kWh of the produced electricity. Substituted energy and allocated share of the minerals required for the gas washing could evolve with a supply mix composed of municipal solid wastes and sewage sludge. Higher co-incineration ratio and moisture, reduce the LHV of the mixture and influence the co-combustion conditions as thermodynamic equilibrium and reduce the combustion temperature [10]. Higher temperature promotes the complete combustion and reduces the CO concentration which is a contributor to the TOPP impacts. Heavy metals and alkaline earth metals present in the sludge and urban wastes could be also sensitive to the running time and efficiency of the incinerator [27,28]. Their quantity should be considered also in the impact analysis. Future work will be able to analyze these effects and evaluate the data's quality using other generic LCA models from databases such as Ecoinvent [29] and data from the simulation [10].

The recycling potential of nutrients contained in the wastewater improved the sustainability index of the WWTP and reduced the impacts of synthetic fertilizer use. It is considered to be a step towards a more sustainable society [30,31]. The production of synthetic fertilizers mainly uses natural gas and phosphate ore and it is energy intensive and contributes highly to the global and regional impacts [32]. This contribution is expected to increase due to the growing food needs. The amount of substituted synthetic fertilizers depends on the nutrient contents of nitrogen and phosphorus in the sludge, the availability for plant, the agricultural soil environment, the nature of the crop, and the growing season [11]. It depends also on the restrictive standards taking into account the risks of micro-pollutant contamination, inhibition, and leaching caused by phosphorus. The spreading of sludge has toxicity effects due to heavy metals [33,34] that should be therefore proven for Algerian sludge. This could strengthen the Algeria regulation of agricultural spreading which is not yet established. It could also encourage farmers which are still reluctant to recycle sewage sludge. The availability of nutrients in the sludge depends on the nature of existing WWTP, the processing changes to be adopted in relation to possible future amendments. Future work should take into account the increase in the treatment capacity of WWTPs and denitrification since the standards on nitrates and total nitrogen have remained below the standards aimed at protecting sensitive areas. This additional process could consume other types of chemicals for a carbon intake. The use of software like GPS_X for modeling would be interesting to compute the inventory analysis and for good data accuracy, however, the uncertainty analysis should accompany the study.

Technically, agricultural spreading is better than co-incineration and effective for the recycling of phosphorus.

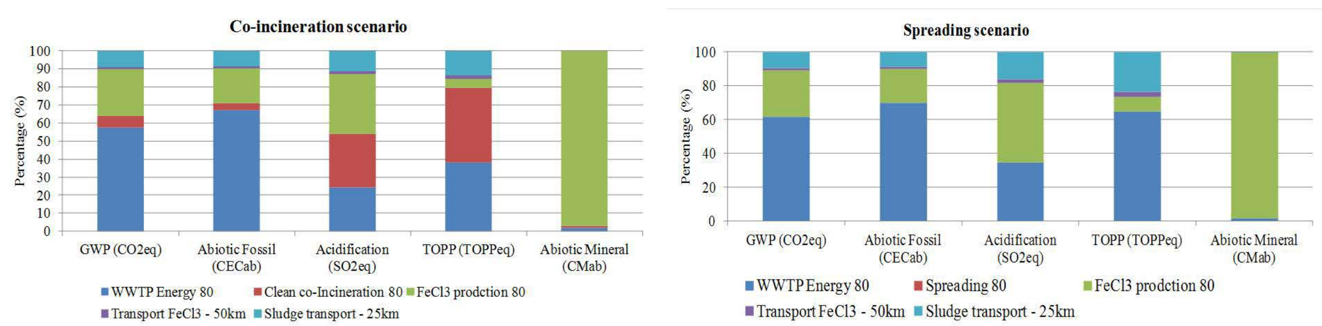

Fig. 8. Processes contribution in the direct impacts of the co-incineration and spreading scenarios.

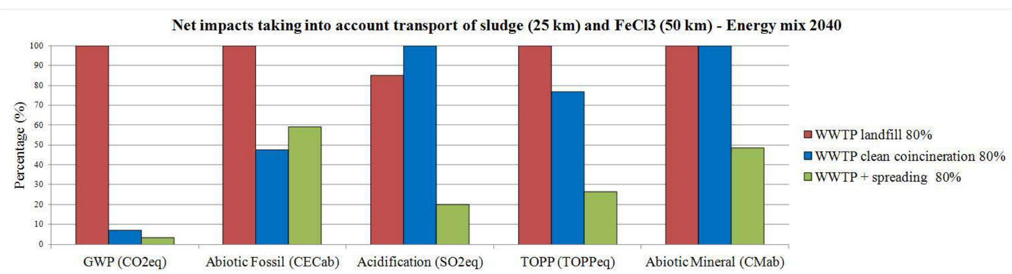

Fig. 9. Comparison of the net potential impacts of scenarios taking into account transport (Horizon 2040).

But further analysis should be realized regarding the impacts of fermentation and mineralization of sludge during storage and spreading. The choice between co-incineration and agricultural application will depend on what we want to save, fossil energy, or minerals, regardless of the regulations in force or other more restrictive regulations. LCA results showed that the co-incineration was better than sludge spreading on the basis of CEC_{ab}. The economic context of Algeria based on the export of primary energies makes the option of co-incineration with cogeneration more attractive than agricultural application. The waste energy recovery has become a priority in developed countries as a renewable energy source. Denmark and Norway are part of the top four European countries in waste-to-energy sector [35], although their economy is partly based on the export of primary resources. This study should be completed by an economic analysis. Reducing nitrogen in the sludge would improve its calorific value and reduce the minerals consumption in the $DeNO_x$ operation if co-co-incineration was chosen. Reducing excessive use of detergents and their phosphorus content, on one hand, and on the other hand by an optimized or reduced use of synthetic fertilizers by farmers, could be the cause of a lower concentration of phosphorus and nitrogen in wastewaters. As an outcome, the amount of chemicals and sludge would be scaled down as well as the nutrient contents of the sludge producing a small substitution effect on synthetic fertilizers, which would promote co-incineration. The bi-functional recovery in the incinerators would be also a possible new alternative allowing energy recovery of the sludge and recycling of materials and nutrients contained in the by-products [27,35].

To cope with future regulatory restrictions, it would be necessary to find which modifications to be made to existing WWTP systems and the types of new WWTP to be installed. For instance, if anaerobic digestion would be useful in the Algerian context by taking into account the whole chain. In temperate countries, spreading digested sludge has proven to be the most accepted solution better than incinerating thickened sludge [21]. It ensures the substitution effect of heat and electricity recovered from biogas of digesters. The choice of co-incineration should be proven in the case of optimizing the management of urban wastes with the reduction of packaging and the improvement of recycling materials. The study of sludge handling with urban wastes in composting or anaerobic digestion in large scale should be as well studied. Improving the environmental index of urban wastewater systems would depend on minimizing sludge at the source and reusing it as useful resources [7], and consequently, updating possible and future regulations. These would be the contribution in future work.

5. Conclusions

This study showed that the regulation amendment increased global and regional impacts of the WWTP of Guelma City. The study was conducted taking into account the final sludge elimination. The spreading and co-incineration benefice was reduced on the basis of LCA results considering direct impact and substitution effect but both were still the best strategies. These strategies depended on the capacity of wastewater treatment systems to control the nutrient content and heat value in the sludge. The impacts resulting from WWTP modification were different according to system boundaries, taking into account the sludge elimination, the availability of chemicals in the economic context, and the transportation impact.

The spreading strategy is largely depended on the nutrient availability and health safety policy concerning the sludge handling. It depends also on the national economic context, particularly on which resource we prefer to substitute, the fossils, or the ores. The spreading could replace the ores used in the synthetic fertilizer manufacturing and could reduce the regional impacts of acidification and photochemical oxidation. The co-incineration was better than the spreading on the basis of the cumulative primary energy consumption and it was competitive for the global warming potential impact. Energy recovery substituted the consumption of fossil fuels, in particular natural gas, the main energy carrier in the studied system. In addition of this, the share of minerals required for the reduction of exhaust gases and $DeNO_x$ operation was negligible with the new amendment in comparison to the reference scenario and to the total consumption.

Improving the sustainability index of urban wastewater systems would depend on minimizing sludge volume and nutrient content. Future studies will need to analyze which final sludge disposal strategy is to be adopted in the national context turn on the nature of the existing WWTP, the processing changes, and essentially on the possible updates of current and future regulations.

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