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APPLICATION OF BASIC OXYGEN FURNACE (BOFS) IN AGRICULTURE: A STUDY ON THE ECONOMIC VIABILITY AND EFFECTS ON THE SOIL

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Abstract

Slags are the main by-products from steelmaking cycle, which are currently recycled inside the steel industry as well as in other sectors with significant environmental and economic benefits. As in Italy slags application is not yet allowed in agriculture, the paper aims at evaluating the technical and economic feasibility of a slag treatment plant, to obtain a product to be sold in the fertilizer market as soil amendment. A preliminary assessment of the fate of some trace metals (Cr, V, Sb and Se) contained into the Basic Oxygen Furnace (BOF)slag, was performed, to analyze the effects on cultivated soils, particularly in neutral/sub-alkaline ones. A soil infiltration column test was performed, assessing the effect of three slag doses (0, 6 and 20 mg kg^{-1} of soil) on two sub-alkaline soils (a clay loam and a sandy loam). A simplified Life Cycle Cost analysis and an estimation of some financial indicators were developed considering the convenience of the investment when the slag is stored internally or externally from the steelworks. The results of the column tests showed an increase of P availability and Ca content, while trace metals (e.g. Chromium and Vanadium) were not leached and mostly remained in the topsoil. This can represent a limit for using slags in the long term. The economic analysis revealed that the convenience on such investment strongly depends on the cost of disposal and on the prices of the slag as fertilizer, and, according to the sensitivity analysis, the profitability is sensitive to the used discount rate.

Key words: column test, converter slag, economic feasibility, fertilizer, payback period

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1. Introduction

In order to promote its sustainability, the steel industry is trying to improve its production cycle according to the "three Rs" approach: *Reduce, Reuse* and *Recycle*. In particular, during the main production processes large amount of residues and by-products of various compositions are daily produced. Over the past few years a material efficiency rate of 97% was reached worldwide (World Steel Association, 2008). A lot of by-products (e.g. slags, sludges and dusts) result from the iron and steel production. In particular, 400 and 200 kg t^{-1} steel of by-products are generated in the integrated steelmaking cycle and in the electric route, respectively (World Steel Association, 2008).

Slags represent 90% of the total by-products, including Blast Furnace (BF) slag, steel slags and secondary metallurgy slag. Steel slags originate from Basic Oxygen Furnace (BOF) and from Electric Arc Furnace (EAF). Steel slags are used in different fields of applications, as shown in Fig. 1 (Euroslag, 2012), such as road construction, cement industry, civil engineering, internal landfill cover, CO_2 sequestration

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(Polettini et al., 2016), soils amending and reclamation otherwise they are disposed in landfill (Rex, 2003). For instance, in a recent study, good results have been achieved by using by-products from different industries, including EAF slag, as substitutes for conventional natural aggregates for road foundations (Pasetto and Baldo, 2018).

In 2012, the use of steel slag in Europe amounted to about 24.7 million tons and about 13% of produced steel slags were disposed in landfill (Euroslag, 2012), but the available land used for land-filling large quantities of slags is reducing all over the world and consequently the disposal cost becomes increasingly higher (Reuter et al., 2004). Thanks to the increase of slag recovery and re-use, a part of such costs would certainly be reduced and the recycling of the slags becomes an attractive alternative in order to minimize the costs and save natural resources (EC, 2012; Reuter et al., 2004).

It is important to provide a holistic approach which balances environmental pollution concern and waste recycling. On this subject, the combination of technology and economic parameters dynamic modelling has allowed the implementation of an eco-efficiency decision support system for of end-of-life solid waste recycling (Avsec and Kaučič, 2018). Nevertheless only few studies are based on a holistic approach to assess the possible by-products reuse. In a recent study, advantages and disadvantages of different pre-treatments, processing and recycling routes were taken into account. By using process modelling, simulation and optimization techniques, the possibility to improve the by-products reuse has been highlighted (Matino et al., 2017).

Slags mainly contain CaO, Fe, SiO_2, MgO and MnO. In particular, the content of CaO, MgO and MnO can be used in iron and steel processes as fluxes (instead of limestone and/or dolomite) and this can produce costs saving. Because of the variable composition of slags, modelling and simulation tools have been developed to simulate and assess the feasibility of steel slags internal recycling, as replacement of lime and dolime (Matino et al., 2018).

The use of steel slags in agriculture is not new, because of their liming properties (i.e. the capability to increase soil pH) (Kühn et al., 2006; Masud et al., 2014; Rodriguez et al., 1994) and their macro- and micro-nutrient supply. It has been shown that the liming effect of Basic Oxygen Furnace Slag (BOFS) is comparable with the commercial limestone (Branca and Colla, 2012). According to EUROSLAG (http://www.euroslag.com/), the use of ironmaking and steelmaking slags as fertilizer, were about 3% of the total slags produced, as shown in Fig. 1. In addition, slags contain large amounts of Calcium (Ca) and Magnesium (Mg) and to a lesser extent Iron (Fe) Copper (Cu), Zinc (Zn), Boron (B) and Cobalt (Co), that are macro- and micro-nutrients for plants (Cha et al., 2006). More recently, it has been shown that slags can help to reduce the sodium content in saline-sodic soils (Pistocchi et al., 2017). Nevertheless, the presence in slags of trace metals, such as Chromium (Cr) and Vanadium (V), which are the major trace elements in slags, can cause potential problems. In particular, the accumulation of heavy metal is a key issues for plant and soil.

A recent study has been focused on plants growing on potentially contaminated areas of landfill body and on their potential metal accumulation (Vaverková et al., 2018). In fact their supply to the soil can lead to significant increase of concentration and bioavailability in the topsoil or to leaching to groundwater (De Windt et al., 2011), especially where soil organic matter content is low. Previous studies, based only on the leaching behavior of slags, have shown that some elements (e.g. Chromium, Cadmium, Arsenic, Lead etc.) are strongly bound to the slag matrix, with the result that they are not released and therefore they are not easily leached (Geiseler, 1996; Proctor et al., 2000).

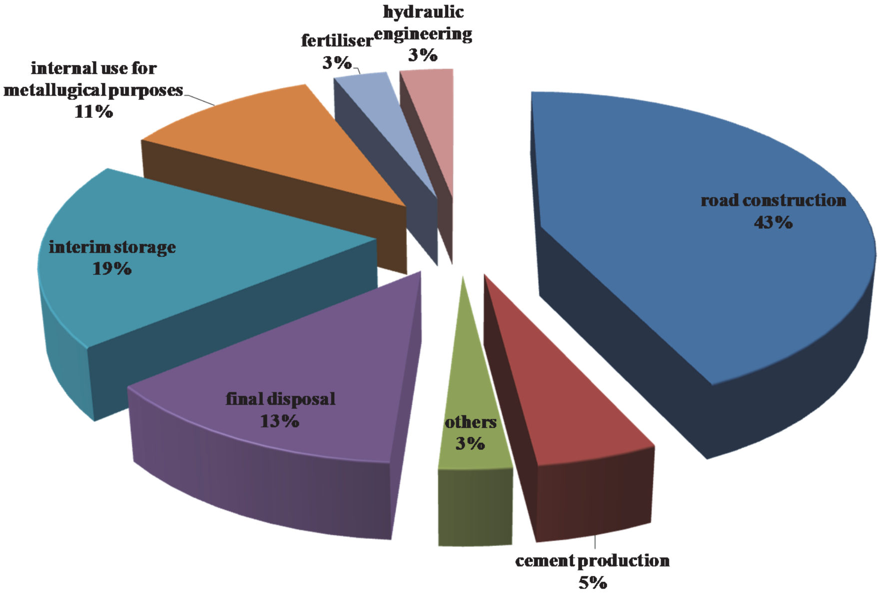


Fig. 1. Use of steel slag in Europe in 2012

Vanadium can be removed from BOFS by microorganisms (Mirazimi et al., 2015). In addition, recent studies have showed that anion exchange resins can efficiently remove V from steel slag leachate in batch and column tests (Gomes et al., 2017). However, trace metals can represent an issue for slag application on cultivated soils (Larsson et al., 2015) due to their toxicity to plants and microorganisms. For example, the toxic effects of V on tomato seedlings (with V supplied as vanadate) depends on the soil type (Larsson et al., 2013; Smith et al., 2013). As far as the chromium is concerned, only low amounts of its hexavalent form Cr(VI) are present in BOFS (Chaurand et al., 2007). On the other hand, the Cr(III), which is more stable in soils, can inhibit root and shoot growth of selected species, at concentration as low as 100 mg kg^{-1} soil (Lopez-Luna et al., 2009). More investigations are required to assess the accumulation of trace metals or their leaching to groundwater once the slags are applied to soils.

Concerning the slag use as fertilizer material in Europe common regulations do not exist, although some countries have their own legislation. In Italy the use of slag as fertilizer is not allowed. The different approaches of European countries towards the use of slags as fertilizer are also due to pedological factors (Morillon et al., 2015). In northern Europe soils are acidic and slag is used as liming agent; in southern Europe, such as in Italy, neutral and sub-alkaline soils are more frequent, which do not require liming agents (Morillon et al., 2015). A proper assessment of the feasibility and convenience of investments in this direction for the Italian context is currently missing, although it would be needed for possible future applications of slag in the fertilizer market. Moreover, the possibility of selling it to other countries when the application of slag in agriculture is already a consolidated practice, can be taken into account.

The work presented here is a first assessment of the possibility to produce BOFS suitable for agricultural purposes in the Italian context. This includes two components: i) a preliminary evaluation of the risk associated to the presence of trace metals in slags done through a column test and ii) a rough economic and financial analysis considering some further treatments of a selected slag fraction to be sold into the fertilizer market. The convenience of such investment has been investigated comparing the cases in which BOFS is stored in internal or external landfills. The study contains some significant features of novelty.

Only few studies investigated the effects of slag application on neutral and alkaline soils (Branca et al., 2014; Morillon et al., 2015; Pistocchi et al., 2017; Wang and Cai, 2006) as well as the leaching behavior of slags with laboratory tests (Motz and Geiseler, 2001) and through soil infiltration column tests (Pistocchi et al., 2012). In this study the mobility of selected trace metals in the profile of two sub-alkaline soils (pH= 8.3 ± 0.5) mixed with slags was assessed.

A “worst case scenario” approach, reproducing the worst conditions (e.g. no plant cover) according to a very preliminary assessment of risks, has been adopted.

The economic analysis has been carried out by developing a simple Life Cycle Cost (LCC) methodology, which takes into account the initial phase of the costs of the project as well as all the costs arising from operating and maintaining during all the economic life of the investment (Bradshaw et al., 2005; Fuller and Petersen, 1996; Greeff et al., 2004). The cost of ultimately disposing/decommissioning was not taken into consideration, as no data were available. However, according to Norsok Standard (1996), in many cases a LCC can be performed by considering the major cost elements. Through LCC, the expected future costs are transferred to a base year by the use of the present value method in order to compare them in a proper way (Bull, 2003).

Generally, LCC is a tool used in decision-making in order to select the best option among different investment values, and, according to Mithraratne et al. (2007), LCC can be used also to assess new materials and new technology as well as to reduce the total project cost. In this study only the investment, the operating costs as well as the saving/revenues arising from the investment have been taken into consideration. LCC have been used by Martinez-Sanchez et al. (2015) in order to provide a detailed and comprehensive cost model for all the key technologies within the waste management system. Gluch and Baumann (2004) have discussed the theoretical assumptions and the practical usefulness of the LCC approach in making environmentally responsible investment decisions. A techno-economic analysis and the calculation of some profitability criteria have been developed by Vlysidis et al. (2011), who compared four different bio-refinery schemes. Thanks to the LCC analysis and the PayBack method, Mahlia et al. (2011) have investigated the existing lighting system by applying energy efficient lighting system in the University of Malaya.

In addition, a break-even analysis procedure to determine the minimum quantity level of production necessary to cover all the cost along the life of the investment has been calculated. A financial analysis of the investment capital budgeting has been also carried out through an estimation of the annual cash flows and an assessment of the discounted cash flows. Moreover, some financial indicators, such as Net Present Value (NPV), Simple Payback Period (SPBP) and Discounted Payback Period (DPBP) of investment, as well as the Internal Rate of Return (IRR) have been calculated. A sensitivity analysis of the NPV variations has been carried out as well.

The paper is organized as follows: in Section 2, the methodologies used for the column tests as well as for the economic and financial analysis are presented. The main results are shown in Section 3. The discussion of the obtained results and the conclusions are summarized in Section 4.

2. Material and methods

2.1. Column test description

Crushed and sieved slag, coming from BOF process, was used in a column infiltration test (Schuwirth and Hofmann, 2006). The crushed slag was sieved in order to have a particle diameter from 0 to 30 mm and its chemical characteristics are summarized in Table 1. The study was carried out with an equipment consisting of 12 Plexiglas columns, 1 m high and with an inner diameter 10 cm. Their bottom was perforated to allow the drainage of water. Three slag doses, *D0* (without slag), *D1* (6 mg kg^{-1}) and *D2* (20 mg kg^{-1}) were homogenized and mixed with two soils, a clay loam (CL) and a sandy loam (SaL) soil. The leachate was collected in a PET tank was placed below each column. The soil was stabilized and brought to field capacity 48 hours before starting the leaching treatment. Columns were then eluted top-to-bottom and in continuous with ultrapure water by means of a peristaltic pump. The elution treatment was carried out until reaching 1.7 liquid to solid (L/S) ratio, corresponding to about 1700 mm, or 2.5 years of rainfall related to the area of reference (coastal plains of Central/South Italy). Drainage was sampled 5 times at 0.2, 0.3, 0.7, 1.2 and 1.7 L/S ratio. At each sampling, aliquots of drainage were collected for the analysis of target parameters and a field blank of deionized water was included. All samples were stored at 4°C and analyzed within one week of collection. At the end of the elution treatment, the soil was collected, stored at 4°C and analyzed.

Table 1. Characteristics of BOFS used in column experiment

Parameter/Element	*Unit*	*Concentration*
EC	mS cm^{-1}	7600
pH	-	12.80
FeO	%	29.10
SiO2	%	12.84
Al_2O_3	%	3.86
CaO	%	42.72
MgO	%	3.86
MnO	%	7.32
S	%	0.13
Cr	mg kg^{-1}	2700
CrVI	mg kg^{-1}	<0.5
Sb	mg kg^{-1}	37
Se	mg kg^{-1}	28
V	mg kg^{-1}	698
Cl	mg kg^{-1}	1330
NO_3	mg kg^{-1}	<10
P	mg kg^{-1}	827

In order to assess the potential environmental impacts of slag application, the following target parameters were considered: Electric Conductivity (EC), pH, total Cr, CrVI, V, antimony (Sb), selenium (Se), chlorides (Cl). Cl was selected as it can have a specific toxic effect on crops and as a reference element for leaching, as it is very mobile in the soil. Furthermore exchangeable cations (Ca_e, Mg_e, K_e, Na_e), were analyzed in soil as indicators of positive effect on fertility, as well as Cation Exchange Capacity (CEC) and plant-available phosphorus (P_{Olsen}). All listed parameters (unless those specific of soil) were analysed in the soil, before and after treatment and in the leachate.

To assess the accumulation in the topsoil total metals were determined, according to a “worst case” approach, which considers also the pools not immediately available to the plants or microorganisms. The same analytical methods used for the liquid matrix were used for the determination of anions, cations and metals, with the addition of hot. Microwave acid digestion was used for the extraction of total metals from soil, while CrVI was extracted by alkaline digestion. Exchangeable cations were extracted using the triethanolamine buffered barium-chloride method. The metals concentrations in the extracts and the exchangeable cations were analyzed at the ICP-OES (Perkin Elmer, Optima 2000 DV). Soil pH and EC were measured in 1:2.5 and 1:5 soil/water suspensions respectively. Available P was measured with the Olsen method (Olsen et al., 1954). To assess the risk of leaching, the percentage of compounds leached with respect to the total pool (soil pool + quantity added with the slag) was calculated. A 1-way ANOVA was performed for each soil to analyze significant differences and the Tuckey HSD test was used for post hoc comparisons (software R, R Foundation for Statistical Computing, http://www.r-project.org).

2.2. Implementation assumption

On the basis of the results of the column test, the economic viability of investing in a slag treatment plant, which transforms a by-product in a product to be sold in the fertilizer market, was investigated. Such project could generate extra revenues and savings for the company from a material that would be otherwise landfilled.

The preliminary economic assessment was carried out by considering the main factors that can affect the use of this by-product from the economic perspective. Starting from the current BOFS management, possible further processes have been subsequently proposed as well as their economic viability. During the melting process in the BOF, along with hot metal, scrap and O_2, fluxes (e.g. limestone and/or dolomite) and slagging agents are added to remove impurities. The main products resulting from the BOF process are steel and BOFS (Fig. 2). BOFS valorization requires a thorough physical and chemical characterization. Currently this slag, before its use and recycling, is tapped, discharged onto the slag yard and subjected to a controlled cooling with water. Further processing consists of crushing, sieving and of subsequently iron removal through magnetic drum separators. The step of sieving consists in the subsequent separation of the various sizes. These fractions, after selection of the metal fraction and particle size, are used in BF as fluxes or recovered in external plants, where they are partially used in the preparation of material for road construction and bituminous mixtures as well as recovered in the cement production.

Some further processes, in order to make BOFS suitable for agriculture purposes, were considered. As shown in Fig. 2, the fraction of BOFS would require further physical and chemical characterizations, an additional screening process, with mobile systems (purchased or rented), followed by drying and packaging. These processes were analyzed from the economic perspective. This could result in reducing the fraction of BOFS currently disposed.

2.3. Economic analysis

The economic analysis has been performed through a simplified LCC. The costs categories considered in this analysis were the investment cost and the annually operating costs (and savings). The total investment cost was based on a rough estimation of the following elements:

- Civil engineering (shed, storage bins, screening, storage silos for processed slag, packaging equipment);
- Technical systems (electrical system, plumbing system);
- Equipment (cranes, trucks);
- Insurance (1% of the investment).

The main consumption of the plant (i.e, energy, raw materials) as well as the necessary manpower and maintenance cost were estimated and included in the calculation of the operating cost. According to the life span of the investment, the present value of the future cost elements was estimated by using the formula of NPV method (Gluch and Baumann, 2004; Lopez et al., 2012) (Eq. 1):

$$LCC_{tot} = IC + \sum_{k=1}^{N} \frac{C_{(k)}}{\left(1+r\right)^{k}} \tag{1}$$

where *IC* is the total amount of the investment cost, $C_{(k)}$ is the sum of all the relevant discounted future cost, minus the saving costs and revenues from the selling of the product occurring in the year *k*, *N* is the life time of the investment (expressed in years) and *r* is the discount rate.

The present value of the estimated cost annually, LCC_{year} needs to be multiplied by a yearly factor (Dong et al., 2014; Lopez et al., 2012) (Eq. 2):

$$LCC_{year} = LCC_{tot} \cdot \frac{r}{1-\left(1+r\right)^{-N}} \tag{2}$$

In order to obtain LCC per unit (per ton of slag), LCC_{year} has to be divided for the estimated annual slag production. From an accounting perspective, a rough identification of the minimum quantity of slag to be produced by the breakeven analysis could be a useful indicator for the investment decision making).

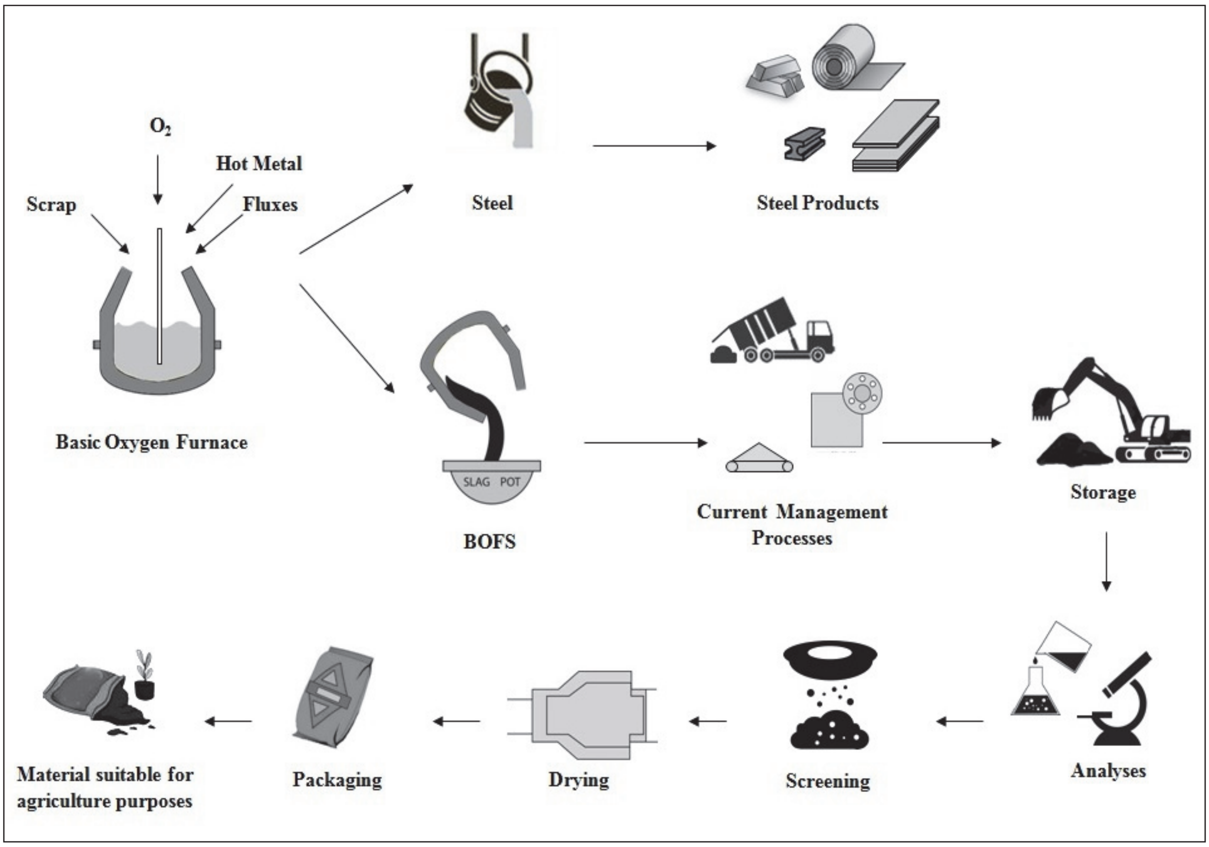


Fig. 2. Scheme of current and further BOFS management

The break-even point of equilibrium (Q*) was calculated (Eq. 3), as follows (Hirschey, 2009):

$$Q^* = \frac{FC_{(k)}}{UP_{(k)} - UVC_{(k)}} \qquad (3)$$

where $FC_{(k)}$ is the annual fixed cost (considering also the investment depreciation amount), $UP_{(k)}$ is the average unitary price and $UCV_{(k)}$ is the Unitary Variable Cost at the year *k*. In this particular case, $UP_{(k)}$ is represented by the unitary saving from the disposal cost and the unitary price of slag as fertilizer.

2.3.1. Profitability analysis

A financial assessment is important to evaluate the viability of a project, since it considers in which way the investment can be financed and how the expected positive and/or negative future cash flow are generated. If, at the end of the economic life, the cash flow is positive, there will be a creation of value for the company; otherwise more resources than the available ones will be consumed. When $k=0$, there is a negative expense of the investment outlay generally sustained with capital equity. Starting from the 1st year until all the operating life of the investment, two types of cash flows were calculated: the operating cash flow, named "Free Cash Flow for the Firm" (*FCFF*), and the "Free Cash Flow to common Equity" (*FCFE*). The FCFF is defined as the cash flow available to the company's suppliers of capital after all operating expenses have been paid and necessary investments in working capital and fixed capital have been completed. To calculate FCFF, different equations may be used depending on what accounting information is available (Stowe et al., 2013). In this paper, the value of the FCFF at year *k* was computed (Eq. 4):

$$FCFF_{(k)} = OP_{(k)} + D_{(k)} \qquad (4)$$

where $OP_{(k)}$ is the operating profit after taxes, but without any consideration for the loan payments, and $D_{(k)}$ is the depreciation cost of the fixed assets of such investment at year *k*.

FCFE was calculated on the basis of FCFF, as it represents the cash flow available for shareholders and equity holders after not only all operating expenses, but also the payments related to the loan (interest and capital debt). FCFE at year *k* was computed (Eq. 5):

$$FCFE_{(k)} = FCFF_{(k)} - (ID_{(k)} + CD_{(k)}) \qquad (5)$$

where $ID_{(k)}$ corresponds to the interest debt and $CD_{(k)}$ is the capital debt related to the loan at the *k*-th year. Thanks to the cash flow analysis, some of the most significant profitability criteria for the measurement of the goodness of the investment, as NPV, PBP and IRR, were calculated (Bas, 2013; Bierman and Smidt, 2012; Brealey and Myers, 2011; Schwab and Lusztig, 1969). NPV discounts all the cash flows at the present value, PBP gives a measure of the time to recover the investment and IRR represents the discount rate at which all the future cash flows (positive or negative) deriving from a project equal the initial investment sustained at k=0 year. NPV of an investment at a fixed time *k* represents the sum of FCFE generated at a fixed interest rate. It is calculated by subtracting the capital outlay, which occurs at the beginning of the project from the present value of the annual FCFE (Dayananda et al., 2002). It can be calculated (Ajah et al., 2008; Van der Laan, 2003) (Eq. 6):

$$NPV = -I_0 + \sum_{k=1}^{N} \frac{FCFE_{(k)}}{(1+r)^k} \qquad (6)$$

where I_0 corresponds to the initial investment outlay.

In the financial analysis the discount rate *r* usually corresponds to the Minimum Acceptable Rate of Return (*MARR*). It is the minimum rate of return on a project that a manager or company is willing to accept before starting a project, given its risk and the opportunity cost of forgoing other projects (Sullivan et al., 2006). If NPV is greater than zero, the investment is profitable and acceptable as the initial investment has been recovered; if it is not positive, the investment should be rejected (Hansen et al. 2009; Park and Sharp-Bette, 1990). Essentially, the PBP can be considered as the period of time required for the project to pay itself (Remer and Nieto, 1995). Among different investments alternative, the PBP-based method allows to identify the investment with the shortest period of capital recovery. As previously described, there are two commonly methods to calculate the PBP: the so-called Simple PBP *(SPBP)* and the Discounted PBP (*DPBP*) (Remer and Nieto, 1995). The SPBP is computed as (Eq. 7):

$$SPBP = \frac{IC}{AOP} \qquad (7)$$

where *AOP* is the Average Operating Profit generated during the period of the investment. The SPBP is easy to compute and gives a preliminary evaluation of the level of the risk related to an investment, but it does not take into account the cash flows after the PBP and it neglects the time value of the money (Bierman and Smidt, 2012; Remer and Nieto, 1995). For such reasons, a more accurate PBP analysis might be needed, which usually is made by means of the DPBP. Such index was proposed by Longmore (1989) in order to tackle some limitations of the SPBP method. The DPBP corresponds to the period by which the cumulated discounted FCFE covers the initial investment expenditure (Yard, 2000).

The IRR indicates the efficiency of the investment and it shows the percentage benefit from a given investment (Akalu, 2001): the higher the IRR, the more attractive the project (Vlysidis et al., 2011). It can be computed as the value of the discount rate that makes the NPV equal to zero in the expiration of the investment (Morera et al., 2015), i.e. by which the following equality holds (Akalu, 2001) (Eq. 8):

$$\sum_{k=1}^{N} \frac{FCFE_{(k)}}{\left(1+IRR\right)^{k}} = I_0 \tag{8}$$

The IRR refers to the return which can be earned on the capital invested in the project: if IRR>MARR the investment is viable (Park and Sharp-Bette, 1990).

3. Results and discussions

3.1. Column test

The analyses on drainage water highlighted the different behavior of chlorides with respect to the other risk parameters. The former, being very soluble, was easily leached from the soil profile. A fast release of Cl was indeed observed. Moreover, for this parameter, a significantly higher accumulation in drainage as a function of slag doses has been detected (Table 2).

The mass balances calculated as the amount of compound leached with respect to the initial soil content (Table 2) showed that, after the entire leaching period (1.7 L/S radio) the amount of chloride added with slags was not completely depleted, particularly in the SaL soil (48 to 58% leached in D2 and D1, respectively in SaL and 71 to 97% in D2 and D1, respectively in CL). This means that some of the chlorides added with the slag can still be found after 2.5 years of average rainfall.

Conversely trace metals were not leached as easily as chlorides. In fact, they can be held by the exchange complexes of the soil, involved in equilibrium reactions with other species in the solid phase or subjected to redox transformations, as the case of Cr. In general, the calculated mass balances (Table 2) showed that only a negligible amount (< 1%) of these elements was leached away from the soil profile, therefore no significant differences due to slag application could be detected in the concentrations of drainage waters (data not shown). However, Sb losses were still detectable, particularly in the SaL soil, although without significant differences ($p<0.05$) due to the slag addition.

Concerning Cr no significant differences ($p<0.05$) were detected among the cumulative losses of D2, D1 and D0 treatments (Table 2), although a high variability was observed among replicates, possibly concealing smaller differences. Cr(VI) was detected only on few samples of drainage waters, mainly from CL soil. Therefore, the total losses of Cr(VI) were negligible in both soils.

Table 3 lists the final soil contents of risk parameters (except Sb and Cl, which were below the detection limit and therefore they are not shown) for the different treatments (D2, D1, D0) and the upper/lower soil layer (U, L).

The concentration of Cr in the soil was significantly higher in D2 and D1 compared to the D0 treatment. However, these values were below the limit imposed by the Italian regulation (LD, 2006). The concentrations of CrVI did not differ among the slag dose treatments. Overall, the results show that trivalent Cr (the majority of Cr in the slag) does not change its redox status and has a higher affinity for the solid matrix tending to accumulate in the topsoil. Indeed it has been shown that trivalent Cr readily precipitates as hydroxide alone or in association with iron or is immobilized by sorption (Banks et al., 2006). This is also confirmed by the fact that no differences were found among the treatments in the lower soil layer (Table 3).

Significant differences in the concentration of V in the soils were also observed, where D2 treatment exhibited the highest V concentration. Such as for Cr, this effect was not transmitted to the lower soil layer, due to the low mobility of V, which is usually retained in soils with pH from 4 and 8 (Cappuyns and Swennen, 2014). This is confirmed also by the results of the drainage water, in which there were no differences among the slag doses treatments. The CL soil showed both at the beginning and at the end of the leaching a higher content of V. The concentration of residual V after treatment in D2 amounted at half of the threshold imposed by the Italian regulation (i.e. 90 mg kg^{-1}, LD, 2006). The effect of slags dose on Se concentration was instead not significant.

Overall, the trace metals applied with the slag accumulated in the topsoil and therefore we concluded that the build up of toxic concentration levels might be the major risk to be taken into account in case of repeated slag applications.

Concerning the positive indicators, due to the very high cation content of the CL soil comparing to the SaL soil, differences among the slag dose treatments emerged only in the latter.

Table 2. Amount of compound leached in percent respect to the initial soil content (soil pool + quantity added with the slag) for the two soils (SaL= sandy loam, CL= clay loam) and the slag alone as a reference

	Slag	***SaL***			***CL***		
	-	***D2***	***D1***	***D0***	***D2***	***D1***	***D0***
Cl	65	48a	58b	84c	71a	97b	100b
Sb	23	3.2	4.4	5.7	1.0	1.1	1.1
CrVI	>>100	<1	<1	<1	<1	<1	<1
Cr_{tot}	36	<1	<1	<1	<1	<1	<1
Se	1.8	<1	<1	<1	<1	<1	<1
V	1.8	<1	<1	<1	<1	<1	<1

Different letters indicate significant differences among treatments

Table 3. Concentrations of risk parameters in soil after column tests, according to different doses of slag application (D0, D1, D2), depth (u = upper layer, l = lower layer) and soil texture (CL = clay loam and SaL = sandy loam)

		Cr		*CrVI*		*Se*		*V*	
		$mg\ kg^{-1}$		$mg\ kg^{-1}$		$mg\ kg^{-1}$		$mg\ kg^{-1}$	
D2	u	92	a	0.74	a	0.51		44.2	a
D1		63	b	0.69	a	0.44		34.5	b
D0		49	c	0.66	ab	0.40		32.5	bc
D2	l	47	c	0.45	b	0.47		28.7	bc
D1		44	c	0.57	ab	0.34		26.7	c
D0		46	c	0.64	ab	0.38		29.5	bc
FA		59		0.66		0.64	a	37.1	a
FS		59		0.60		0.20	b	29.0	b

Different letters indicate significant differences among treatments

In particular, for this soil, the Ca_e content increased in D2, as well as Mg_e content, which was higher in D2. Other experiments with saline-sodic soils have shown the same effect on exchangeable cations (Caravaca et al., 1999; Pistocchi et al., 2017). The main effects on available phosphorus (P_{olsen}) of the soil are due, as expected, to the type of soil, in fact the CL soil contains almost twice of available phosphorus. However, there were also significant differences due the slag addition in the highest dose (D2) treatment, in which the P_{olsen} was higher than in D0. The increase in phosphorus availability, even after intensive leaching, represents a positive aspect already observed in other studies (Kühn et al., 2006), and it is due to either the pH increase in acidic soils or the reactivity of soluble silicates present in the slag. For P_{olsen} the effect of slag is limited to the upper layer of soil, showing the scarce mobility of this element in the soil profile. Further confirmation is due to the fact that in the drainage water the concentration of soluble phosphorus (PO_4) was always found to be below the detection limit.

3.2. Economic and financial results

An exemplar medium-sized steelmaking facility with a production of 4 Mt of Hot Rolling Coils/y (corresponding to an amount of approx. 4,200,000 t of steel/y) was taken into consideration. Assuming a production of 0.125 t BOFS per t of steel (EC, 2012), a production of 525,000 t of BOFS per year is obtained. According to Euroslag (2012), 13%, namely 68,250 t are currently landfilled. 90% of this slag does not show the physical and chemical properties and mechanical features needed to be further treated for use in agriculture. Only the 10% of the slag, i.e. 6,825 t per year, can be treated and reused as fertilizer. The investment amount is estimated around 1,000,000 € and was articulated as follows:

1. Civil engineering: 100.000,00€
2. Technical systems: 250.000,00€
3. Equipment: 550.000,00€
4. Insurance (1% of investment): 100.000,00€

3.2.1. Economic results

LCC analysis has been carried out considering an estimation of lifetime of the treatment plant in 20 years. As far as the operating costs analysis was concerned, the cost of raw materials consists of the electricity cost and bags for packaging, which altogether affect the final cost of the product for 0.20 €/ton. The personnel cost has been estimated considering a staff composed by two workers, one laboratory technician and one supervisor. The total annual cost for both workers is estimated in 44,000 €/year (22,000 €/year per each worker, considering 300 working days per year and an hourly cost of 9 €/h), and the annual cost for the laboratory technician is estimated in 38,000 €/year (considering an hourly cost of 16 €/h). The annual cost of the shift supervisor, which works half time, has been estimated around 16,500 €/year (considering an hourly cost of about 14 €/h). To sum up, the total annual personnel cost accounts for 98,500 €/year, as shown in the Table 4. The cost of the additional laboratory analyses, which must be performed once a month (determination of reactivity, according to UNI EN 13971 and determination of neutralizing value, according to EN 12945:2007) was about 500 €/year. The maintenance cost can be estimated as a percentage of the total investment, which may range from 2% to 20%/year (Fischedick et al., 2014; McKetta Jr., 1981). In this case, a 2% of the total investment, which accounts around 20,000 €/year, has been considered. As far as the estimation of the revenues and savings is concerned, the price of the BOFS as fertilizer ranged approximately from 5 €/t to 25 €/t. In this analysis, the lowest price was taken into consideration and it was assumed that all the produced slag as fertilizer is sold on the market. For the estimation of the landfill, two different costs in case the slag is stored internally or externally from the steelmaking plant were supposed. In case of external disposal, the disposal cost is not high as the slag is not a hazardous material, but an inert one. Considering that the average European disposal cost for the special waste is around 80 €/t (CEWEP, 2014; Fischer et al., 2012), an estimate of the disposal cost can be obtained by applying a reduction of about 25%, resulting in an average disposal cost of 60 €/ton. If the steelworks disposes the slag in its internal landfill, no real expenditure will be associated to the disposal. However there is still an internal cost associated to the use of a soil that could be exploited for different purposes. In this latter case, an average disposal cost, lower than the external disposal cost due to the fact that there are not transport cost and tax, has been estimated at 30 €/ton. Obviously the soil can assume different costs according to the location of the steelworks: the smaller the internal space devoted to landfill, the greater the value of the soil will be. The LCC analysis was carried out considering a 4% discount rate. All the previously discussed operating costs and assumptions are summarized in Table 4.

The results of the LCC per unit (per t of slag) are shown in the Table 5 for both scenarios and are very encouraging, even considering the sensitivity of the LCC outcomes with respect to the quality of the input data (Utne, 2009). In both the above depicted scenarios, it can be concluded that the landfill savings and the revenues were sufficient to cover all the costs generated by the investment.

Fig. 3 depicts the LCC, according to variations of the quantity of slag which is treated and sold as fertilizer during one year.

LCC decreases as the production increases, since revenues and landfill savings were considered. In case of the external disposal, a slag production of about 3 kton allows to cover all the costs, as shown in the Fig. 3, while in case of the internal disposal, a production of about 5 Kton is needed.

Table 4. The operating assumptions and estimated data

	Unit	*Value*
Plant Capacity	ton/year	6,825
Economic Life Investment	years	20
Investment Cost	M€	1,000,000
Operating Cost		
Variable Cost	€/year	1,365
Fixed Cost:		
Total Personnel Cost (2 workers, 1 laboratory technician and 1 part-time supervisor):	€/year	98,500
Total Maintenance Cost (2% of Investment)	€/year	20,000
Laboratory Analysis Cost	€/year	500
Savings and Revenues:		
External Landfill Cost	€/t	60
Internal Landfill Cost	€/t	30
Minimum Slag Price as fertilizer	€/t	5

Table 5. LCC Results

LCC	*Unit*	*External Disposal*	*Internal Disposal*
Investment Cost	€/t slag	+10.8	+10.8
Total Operating and Fixed Costs	€/t slag	+18.9	+18.9
Avoided cost of disposal[a]	*€/t slag*	*-64.4*	*-32.2*
Slag selling as fertilizer[a]	*€/t slag*	*-5.4*	*-5.4*
LCC	**€/t slag**	**-40.1**	**-7.9**

[a] Positive value means cost; negative value means savings/revenues

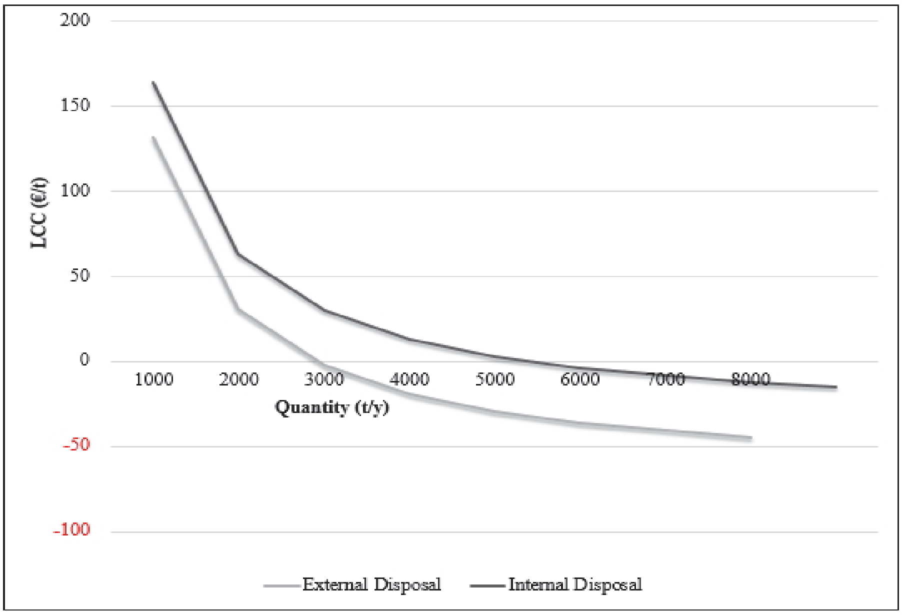


Fig. 3. LCC vs. quantity of treated slag in both the considered scenarios

In the exemplar case considered in the present analysis, the production overcomes 6 kton of slag per year, so it is possible not only to cover the costs but also to have some gains. According to the obtained results, a further important parameter was the plant capacity: if the steel production increases, also the BOFS will increase together with the potential revenues. Moreover, the higher the amount of by-products, which are disposed in an external landfill, the more convenient the investment. On the contrary, for the steel plant which owns a large internal landfill and the value of the soil is below 30€/t, the investment is convenient and viable only for considerable amount of BOFS sold as fertilizer or for high BOFS prices. For instance, in case the cost of the internal landfill is 15 €/t, at least 10 Kton of BOFS/year should be sold as fertilizer and soil amendment at a minimum price of 5 €/t. Otherwise, if the quantity remains the same as shown in Table 4, the slag fertilizer price should increase at least three times in order to cover the costs.

3.2.2. Results related to the payback period

Based on LCC case studies previously explained, an overall financial analysis was developed and NPV, SPBP and DPBP as well as IRR indicators were calculated in both scenarios. The investment depreciation cost was assumed constant during the first 10 years of the investment. The other data remained the unchanged with respect to the values shown in Table 4. An average value of 40% for taxes was considered, according to the Italian regulation. The investment was supposed to be financed in the following way:

- 50% by a long-term loan;
- the remaining 50% will be financed by the company's capital.

The features of the loan used in the analysis are:

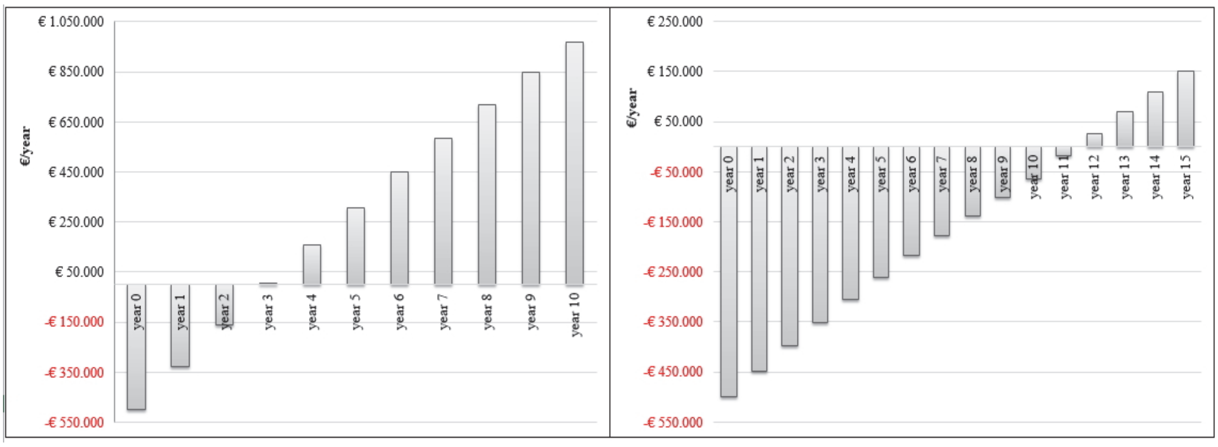
- 5% interest rate;
- 10 years;
- annual and constant installment payment.

The FCFE cash flows were discounted at 4% MARR. The cumulated discounted FCFE in both scenarios are shown in the Figs. 4a and 4b. In order to calculate the cash flows, the positive and negative variations were taken into consideration. At year 0 the negative variation was due to the amount of the capital investment financed by the company's capital.

The main financial indicators, NPV and IRR as well as SPBP and DPBP for both scenarios are shown in Table 6. Such as in the economic analysis, the case of external disposal is the most convenient scenario even from a financial point of view, since NPV is about 2M€, IRR is more than 30% and the time to recover the investment is approximately 5 years. However, the values obtained for the case of internal disposal are still encouraging, since NPV is positive, IRR is more than the MARR and the period to recover the investment is in an acceptable range.

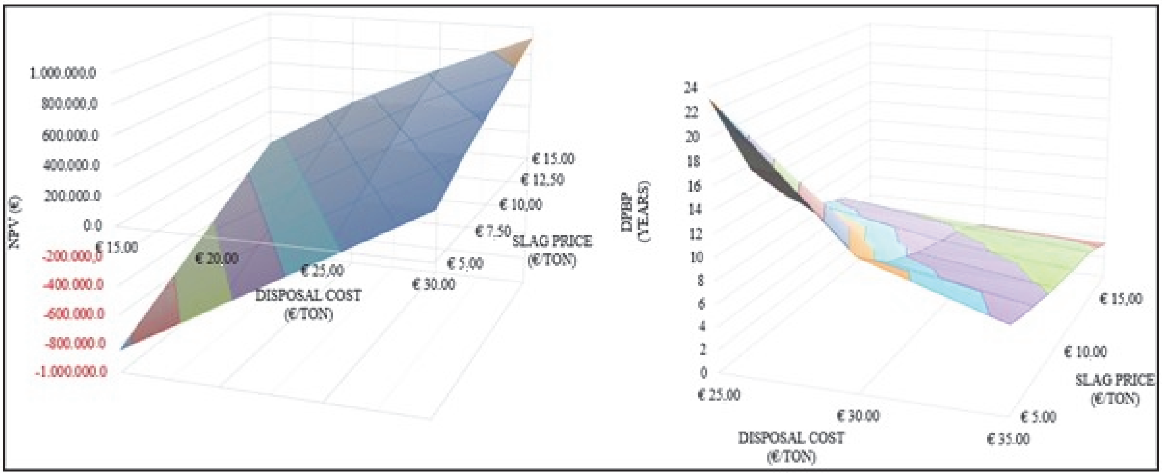
Fig. 5 depicts through a surface graph the trend of DPBP and NPV versus the landfill disposal cost and the selling price of BOFS as fertilizer. For values of the disposal cost around 20 €/t, the NPV and DPBP suggest that the investment is convenient only if the BOFS price is higher than 10€/t. Obviously, the higher the disposal cost and the increase of the slag selling prices, the shorter the time to recover the investment and the higher the value of NPV.

A sensitivity study was also conducted to investigate the sensitivity of NPV with respect to the variations of the discount rate, by keeping constant the value of the other variables. The discount rate represents the time value of money, which depends on inflation, cost of capital, alternative investment opportunities and personal consumption preferences (Mithraratne et al., 2007). It could suffer from the situation of the international market and it is important to understand how its variations can affect the values of NPV and, consequently, the economic viability of the investment. In the present analysis, the discount rate varied from 2% to 14%. The results are shown in the Fig. 6: an increase of the discount rate decreased the NPV values. The NPV results in the external disposal scenario were more sensitive than in the internal disposal, since they rapidly decreased for values of the discount rate lower than 10%.



(a) (b)

Fig. 4. Cumulative discounted FCFE (a) for the first 10 years of the life of investment in case of external disposal and (b) for the first 15 years of the life of investment in case of internal disposal



(a) (b)

Fig. 5. Variations of the DPBP (a) and the NPV (b) vs. variations of disposal range costs and of prices of BOFS as fertilizer

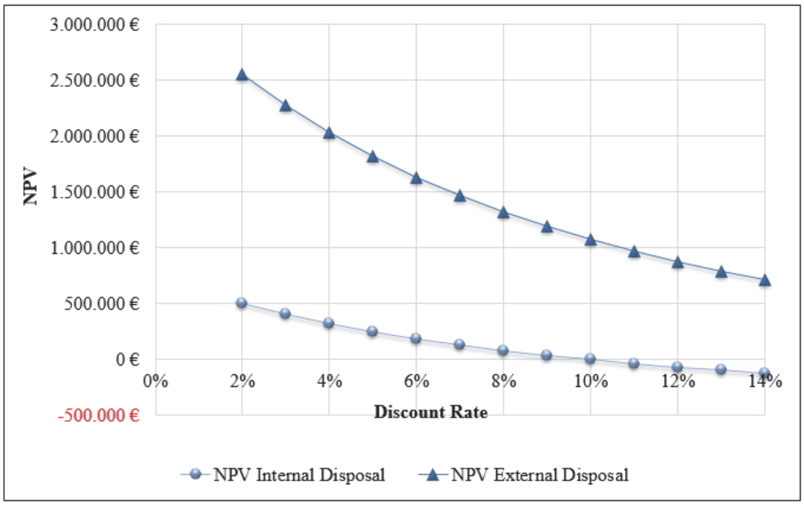


Fig. 6. Sensitivity analysis: NPV with respect to the changes of the discount rate

Table 6. Profitability Indicators of the both cases

	External Disposal	*Internal Disposal*
NPV (€)	2,030,853	325,598
IRR (%)	36%	10%
SPBP (Years/Months)	3.1	8.4
DPBP (Years/Months)	3.0	11.4

Afterwards the curve decreased in a smoother way and the NPV sensitivity decreased. In the internal disposal scenario, large variations of the discount rate were related to small variations of the NPV values.

In case of internal disposal, the investment is viable until the discount rate is lower than 10%, as the NPV shows positive values; in the external disposal scenario, the discount rate can have values even more than 10%.

4. Conclusions

This paper presents a multidisciplinary study aimed at a first assessment of the technical and economic feasibility of the use of a portion of the BOFS produced in the integrated steelmaking cycle for agriculture purposes. In particular, a preliminary evaluation through a column test was made to assess the potential effects related to the leaching or to the accumulation of metals compounds on sub-alkaline soils common in Italian coastal plains. Such investigation was coupled to a LCC analysis and to the calculation of some important financial indicators, in order to assess whether an investment, aimed at commercializing BOFS as soil amendment, would be viable for a steel company. Both direct and indirect costs have been included as well as revenues/savings projections.

The column test showed that chlorides input from slag was almost completely leached in the early phases of the observation period, corresponding to less than a year of rain in the reference area (coastal plains of Central Italy). Concerning trace metals, significant differences due to the slag supply were not observed in drainage waters or in the lower soil profile. This means that such compounds preferentially cumulate in the topsoil, rather than their leaching. In particular higher concentration of Vanadium and Chromium were found in the topsoil treated with the slags. In the long-term this can represent a limit to the use of slag in this kind of soils. On the other hand, at the end of the leaching experiments, some positive effects on soil fertility were detected. A significant increase in exchangeable Mg and Ca was observed in the SaL soil, which is less rich in bases than CL soil. A further positive effect is related to the increase of the P availability, which is found, however, only after the application of the highest slag dose, likely due to the competitive sorption of Si (Prado and Fernandes, 2001; Souza et al., 2008).

The LCC analysis and the financial analysis highlighted the economic viability and profitability of both proposed scenarios. In case of the internal disposal, not only such investment is convenient under some defined conditions, but also it will allow the steelmaking to dedicate the internal spaces for different uses. In case of the external disposal, such investment is convenient since the steelmaking will have some relevant savings from the landfill cost and the project is able to produce cash flows, which pay back the investment in a realistic time.

By considering these results, further investigations should focus on reducing the long-term environmental impact of BOFS, especially through the decrease of trace metals content or availability. The possible agricultural use of slags can contribute to the "zero-waste" achievement, through the consideration of slag as a potential valuable resource. Moreover, this will promote the increase of steel slag recycling and the reduction of its disposal in landfill, with economic advantages for the steel industry and potential opportunities for the fertilizer industries and agriculture.

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