Optical sorting technology for waste management from the Boukhadra iron ore mine (NE Algeria)

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Abstract

Mining processes in the iron ore mine of Boukhadra, Tebessa (NE Algeria) generated thousands of tons of mining wastes every year, which represents a real threat to the environment, leading to hazardous effects for the resident population of the region. The aim of this study is the selective sorting of the Boukhadra mining wastes for valorization. This will facilitate the recycling of the mineral substances (limestone, iron, marls) on the one hand and it makes it possible to minimize the volume of stocks and their environmental impacts on the other hand. To do this, and taking into account the chemical properties of wastes, we recommend an optical separation management using a color camera and a microprocessor linked to the ejection system (valve or pump), the color measurement tests performed on Boukhadra waste rocks samples using Matlab codes converted from Algorithms showed that each rock has a specific color (Red Green Blue value) or RGB. For this purpose, the use of three optical separators that sort according to algorithmic commands (RGB interval) will contribute to the separation of the Boukhadra mining wastes and consequently simplify their reuse.

Keywords: Boukhadra mine, environment, optical sorting, recycling, valorization, mine wastes.

1. Introduction

The releasès from mining are a potential negative source for the environment, sludge dumping, mine drainage, soil, air pollution and many other threatening effects to both environment and human lives (Bouzahzah *et al*., 2014; Benselhoub *et al*., 2015a; Stankevich *et al*., 2015; Idres *et al*., 2017). The management or the zero-waste goal is based on source reduction, repair, reuse and recycling (Topanou, 2012). Going back to the history of ore valorization, a lot of sorting techniques have been used, such as, mechanical sorting (trommel), electrical sorting (Foucault current), magnetic sorting (magnetic separator), radiometric sorting (radius γ) and optical sorting (camera).

The concept of optical separation has already been used for the sorting of seed, wheat, coffee, household wastes (plastics, glasses, papers). Today it is widely used for the sorting of mining wastes. An example of the newly developed optical system at Comex (an optical sorter) allows the identification and separation of the different mineral particles according to their color, resulting in a product of high purity ranging from 99 to 99.9% (Kolacz, 2012).

As a result, based on the interaction results of light with minerals (color), optical separators can play a very important role in the field of integrated mine waste management.

2. Overview on Boukhadra mining wastes

The Boukhadra mine is located in the Jebel Boukhadra Mountain at an elevation of 850 m, with the Mount of Boukhadra constituting the highest part (the peak) with an altitude of 1463 m (ArcelorMittal, 2012). Figure 1 represents a general view of Boukhadra iron mine and wastes generated during the different mining processes.

Figure 1 - General view on the mining wastes from the Boukhadra mine.

Downstream of the mountain, we find the Boukhadra village with more than 11000 inhabitants. The mine case of this study has been mined since Roman times for the extraction of copper, after which exploitation was conducted for zinc and other polymetals. From 1926 until today, the mine exploits the iron ore of the hematite type by two methods: open and underground (ArcelorMittal, 2012). According to their use, iron ore is the most required element in the world, as well as in Algeria. To satisfy the demand for this mineral resource (iron and steel industry, cement plant), the mine must increase the rate of prospecting and exploitation works, which generates, of course, thousands of tons of mining wastes, stored in the form of piles.

This mining waste occupies a large area, and hinders exploitation (truck circulation), and residents are affected by the sliding of the blocks from the mining wastes. Moreover, this waste generates air, water and ground pollution in the form of dust, runoff of the leaching water from mining wastes (especially during rainfall), and infiltration of water contaminated with iron in the soil which consequently affects living beings (humans, wildlife and flowers). The random storage of the mining waste deteriorates the panorama of the region and disturbs the natural life (environment). Some environmental impacts of mining wastes from the Boukhadra mine are discussed in (ArcelorMittal, 2014).

3. Characterization of Boukhadra mining wastes

3.1 Chemical analysis of mining wastes

Two varieties of mining wastes are found in the stockpiles of the Boukhadra mine; waste rocks and other mine wastes (low grade iron ore resulting from the extraction process). Their chemical composition was determined by an XRF analyzer in the Center for the Study and Technological Services of Construction Materials Industry (CSTSCMI) - Boumerdes (Table 1).

Table 1 - Chemical analysis by XRF of mining wastes from the Boukhadra mine.

Element (%) / Samlpe	CaO	Fe_2O_3	SiO_2	Al_2O_3	MgO	K_2O	MnO	SO_3	TiO_2	Na_2O	P_2O_5	BaO	LOI
Waste rocks	34.56	19.97	15.81	6.12	1.25	0.81	0.57	0.02	0.34	0.01	0.11	0.01	17.59
Other	1.77	38.57	30.57	3.65	1.27	0.27	0.89	0.01	0.16	0.1	0.06	0.05	18.84

3.2 Atomic adsorption spectroscopy (AAS) analysis

Atomic Absorption Spectrometry (AAS) is an analytical technique whose objective is to measure the amount of chemical elements (metals) present in a material while measuring the radiation absorbed by this material (García and Báez, 2012). The analysis by SAA of the Boukhadra iron mining wastes was performed at the Office of Geologic and Mining Research (OGMR) – Boumerdes (Table 2).

Table 2 - Atomic adsorption spectroscopy (AAS) analysis of the Boukhadra mining wastes.

Sample \ Element (%)	Ni	Cu	Zn	Pb
Waste rocks	0.010	<0.005	0.012	<0.005
Other	0.020	<0.005	0.006	0.010

3.3 Scanning electron microscope (SEM) analysis

Scanning Electron Microscopy (SEM) is an analytical technique that produces high-resolution images of the surface of a material. When an electron beam sweeps the surface of a sample, this latter emits certain particles; and these particles are analyzed by different detectors and construct a three-dimensional image (Errais, 2011).

The analysis by SEM of Boukhadra waste rocks was done at the National High School of Mining and Metallurgy (NHSMM) Annaba. The SEM analysis shows cut limestone grains ($CaCO_3$), which confirms that the wastes have not undergone acid attack. There are also, microorganisms, silica spherules (SiO_2), alumina grains (bauxite Al_2O_3) sub-rounded and hematite crystallite debris (Fe_2O_3) from which we can guess by the hexagonal forms, that the grain forms indicate prior mechanical treatment because the fragmentation is visible by SEM. In addition, around the grains, other elements were detected by SEM, namely, P, Mg, Ba (Figure 2).

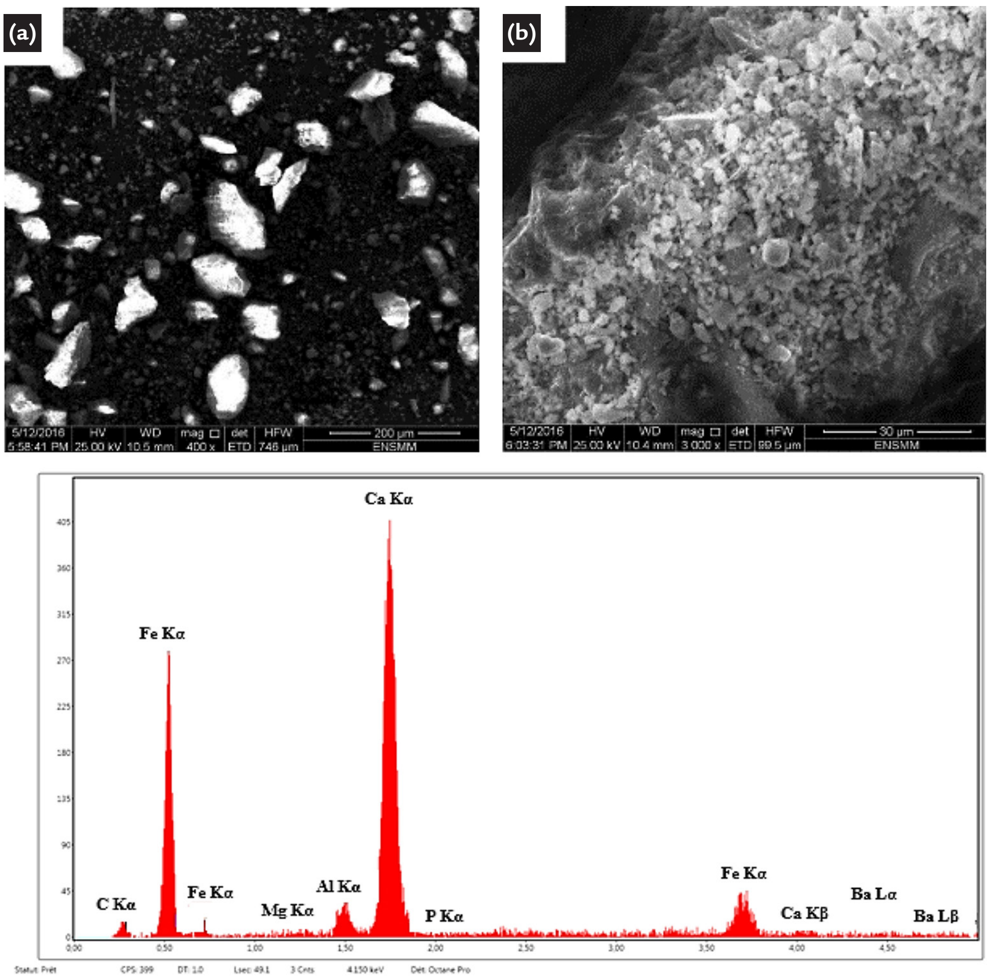

Figure 2 - SEM Photomicrographs for different magnifications of the Boukhadra waste rocks (a: X 400, b: X 3000) and associated spectra.

4. Analysis of drainage water

Three (3) samples of water were collected from three (3) different zones near the Boukhadra iron mine for a characterization of their nature. A chemical analysis of the samples was carried out at the Society of Water and Sanitation of Algiers (SWSAL), and the results are given in Table 3.

Table 3 - Analysis of mine drainage water from the Boukhadra.

	Parameters	Units	Standard	Water Sample			Medium
				(1)	(2)	(3)	
Chemico-physical	pH	pH Unit	≥ 6,5 and ≤ 9	7.05	6.75	7.25	7.01
	Biochemical Oxygen demand (BOD5)	mg/l O_2	7	8.75	6.25	7.5	**7.50**
	Chemical oxygen demand (COD)	mg/l O_2	30	45	31.5	36.1	**37.53**
	Suspended material	mg/l	25	27.1	25.4	24.5	**25.66**
	Sulfates	mg/l SO_4	400	346	284	297	309
	Temperature	°C	25	25	25	25	25
chemical	Ammonium	mg/l	4	1.35	2	2.32	1.89
	Barium	mg/l	1	1.62	1.4	0.9	1.3
	Dissolved iron	mg/l	1	4.5	7.31	9.6	7.13
	Manganese	mg/l	1	0.94	1.43	0.64	1.00
	Nitrates	mg/l NO_3	50	32.2	41.6	26.5	33.43
	Phosphorus	mg/l	10	4.54	9.62	10.78	8.31
	Copper	mg/l	2	0.53	0.32	0.05	0.30
	Lead	µg/l	50	22.3	16.3	31.62	23.4
	Zinc	mg/l	5	1.43	0.94	1.1	1.15

Overall, these analysis results show unacceptable values in relation to the required standards (Official Journal of Algeria 2011). However, some COD and BOD5 values are well above the allowable threshold and the ratio of: COD/DOB5=37.53/7.5=5.004>3.This indicates a high rate of organic matter in this water. Also, this effluent is not degradable (difficult to treat).

High levels of Sulfates and Ammonium (NH_4^+) are also noted, as well as the presence of heavy metals (lead, zinc). Since the high content of metals interferes in the biological treatment of water, they also pose a direct danger to human health. All this shows a chemical contamination of the Boukhadra site water, and consequently, the soils that are in contact; this is in direct correlation with the high contents of ferrous elements (Fe_2O_3) and in Barium ($BaSO_4$).

In fact, water pollution can also lead to soil contamination, and this will affect the water table, the quality of surface and groundwater water, which have direct impacts on animals (polluted grass) and therefore the human health (ArcelorMittal, 2014).

5. Soil analysis

Soil samples were collected in three sites at Boukhadra village closed to the mine, five subsamples were taken in a depth of 0-5 cm within each plot in order to obtain a representative sample, as close as possible to the center of the plot in a homogeneous pedological area (Benselhoub *et al.*, 2015b). The soil chemical analyses are presented in the Tables 4 and 5.

Table 4 - Chemical analysis of soils from the Boukhadra village.

Sample / Element (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Ba	K_2O	TiO_2	MnO	P_2O_5	Pb	S
(1)	31.83	7.62	5.7	23.99	1.13	0.07	0.72	0.64	0.09	0.35	0.01	0.11
(2)	36.63	9.42	17.38	10.4	1.0	0.79	1.29	0.42	0.6	0.16	0.01	0.22
(3)	40.66	11.08	11.57	8.92	0.67	0.74	1.56	0.68	0.41	0.13	0.04	0.21

Table 5 - Analysis by AAS of soils from the Boukhadra village.

Standard (mg/kg)	France (1985) Standard Afnor NF U44-041 (Dhaou-El-Djabine, 2005)	Cu	Pb	Zn
		100	100	300
Sample	(1)	<50	100	120
	(2)	<50	120	<50
	(3)	100	90	110

From the previous results, we observe that the soil of Boukhadra is a little polluted by heavy metals specially, the lead metal (Pb) and a variable concentration of iron. This is due to the infiltration of water contaminated by the iron on the Boukhadra soil, the high rate of silica shows that the soils of Boukhadra are acidic.

6. Manual sorting of Boukhadra iron mining wastes

Before proceeding with the optical sorting of Boukhadra mining wastes, we made a manual sorting of these wastes according to the mineral colors (Figure 3). It is clear that the mineralogical composition consists mainly of: limestone, hematite, yellow and gray marl (Rouaiguia *et al.*, 2017), and the presence of these minerals is confirmed by the XRD analysis.

Figure 3 - Manual sorting of mining waste from Boukhadra.

6.1 XRD Analysis of the mining wastes

The analysis by X-ray diffraction of the Boukhadra waste rocks performed at (OGMR Boumerdes) are given in Figures 4, 5, 6 and 7.

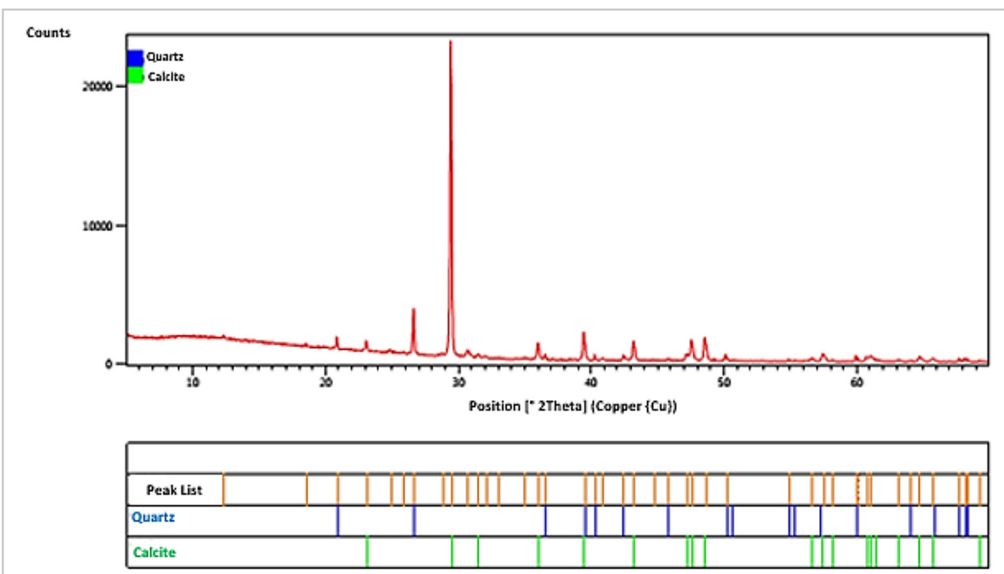

Figure 4 - XRD spectra of limestone.

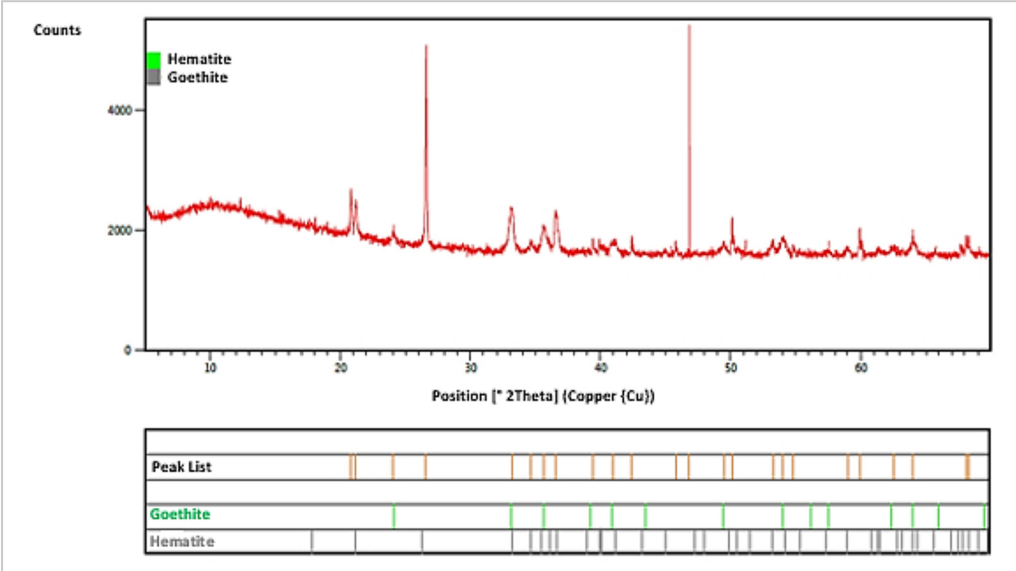

Figure 5 - XRD spectra of iron.

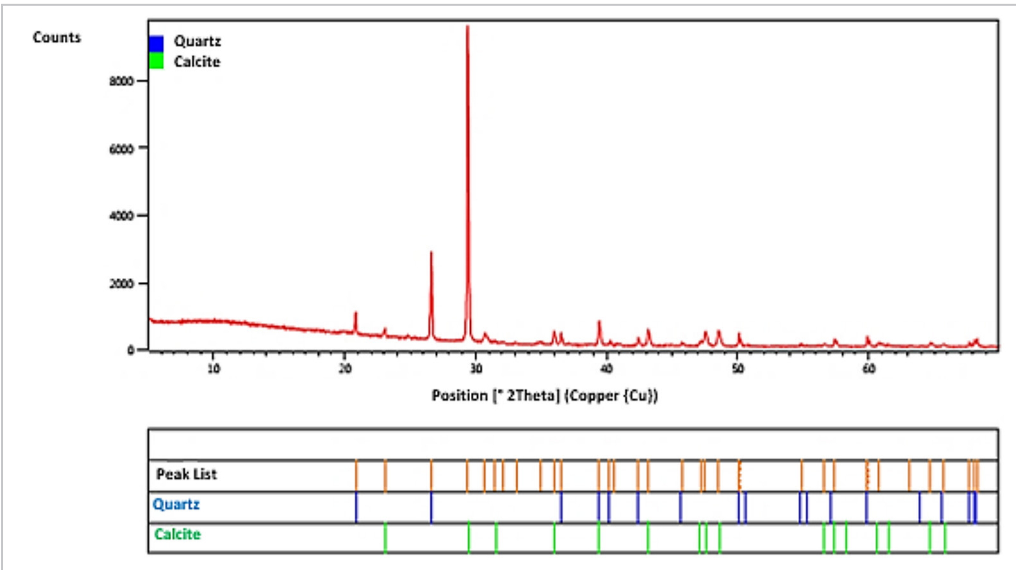

Figure 6 - XRD spectra of gray marl.

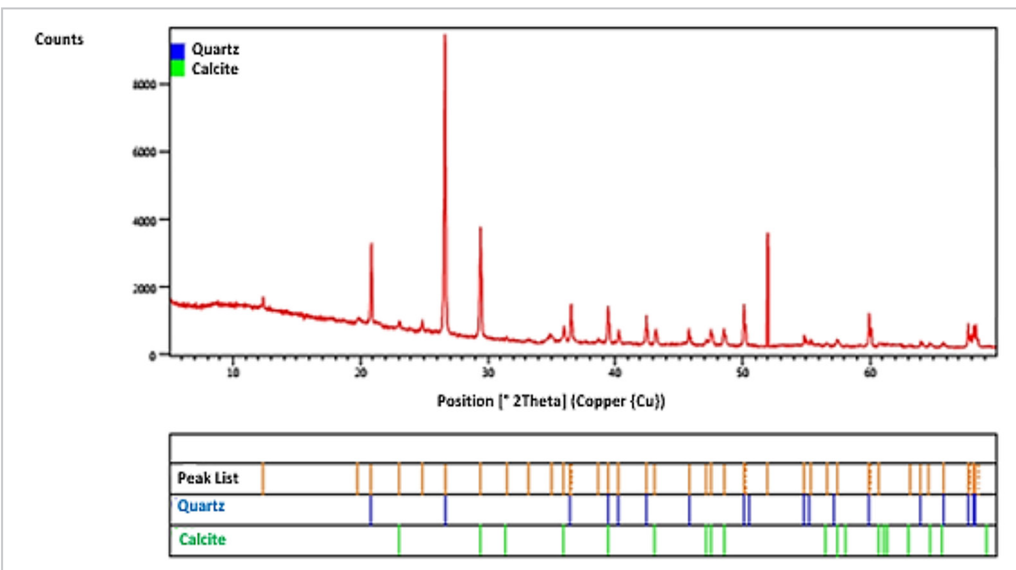

Figure 7 - XRD spectra of yellow marl.

6.2. Chemical analysis of the mining wastes

The chemical composition of the mining wastes given in the Table 6 was carried out by the XRF analyzer at (CSTSCMI – Boumerdes).

Table 6 - Chemical analysis of mining wastes at the Boukhadra mine.

Sample \ Element (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	TiO_2	MnO	P_2O_5	K_2O	Na_2O	SO_3	MgO	BaO	PbO	ZnO	ZrO_2	LOI
Limestone	7.3	1.06	5.62	49.87	0.04	0.02	0.05	0.09	0.2	0.15	1.21	0	0.02	0.01	0	31.38
Iron ore	21.14	3.61	34.32	8.22	0.26	1.06	0.1	0.56	0.05	0.57	0.32	0.12	0.078	0	0	27.54
Gray marl	34.45	8.30	8.46	25.82	0.23	0.01	0.1	0.91	0.01	0.61	1.27	0.01	0.01	0.01	0.17	18.8
Yellow marl	46.26	11.42	10.04	18.45	0.27	0.01	0.13	0.99	0.07	0.73	0.77	0.01	0.01	0.01	0.18	8.7

According to the chemical analyses of these samples, the iron content is 34.32% Fe_2O_3; 21.14% SiO_2; 8.22% CaO and 3.61% Al_2O_3. Limestone is constituted of49.87% CaO. Yellow marl is composed of 46.26% SiO_2 and 18.45% CaO against 34.45% SiO_2 and 25.82% CaO in the gray marl.

For better understanding of the qualitative and quantitative aspect of this material, taking into account the color of the minerals, we proposed the management of these mining wastes by optical sorting (colorimetric separation).

7. Management of mining wastes by optical sorting

Ore treatment and integrated management of mining wastes play a key role in the field of mining industry by reducing the large volumes stored on the tile and by facilitating their reuse in various economic sectors, and in the restoration or the rehabilitation of mine sites (Boudra *et al*., 2015). To do this, colorimetric measurements are performed on different samples of the Boukhadra mining wastes for their separation by an optical sorter.

7.1 Principle of optical sorting

According to Manouchehri, 2003, the optical sorting process is one of the most efficient and economical cost-saving techniques that can be used for secondary wastes treatment, separation and recycling. This will minimize investment costs, limit the environmental impacts of mining wastes and improve the quality of the ore. The optical separator is mainly constituted of the following sections (Suhasaria and Pathak, 2012):

Feeding: The crushed feed material is transported to the point where the optical data is collected.

Collecting optical data: The ore must pass through an optical sensor system (color camera), the reflected light of each particle is detected and processed.

Optical data processing: Optical data processing is performed by an electronic processor; appropriate signals are transmitted to the mechanical system for the separation of materials.

Mechanical separation system: according to the instructions given by the processor, the mechanical separation system consists of a valve or a compressed air rejecter, which sorts.

More illustrations are given in Figure 8.

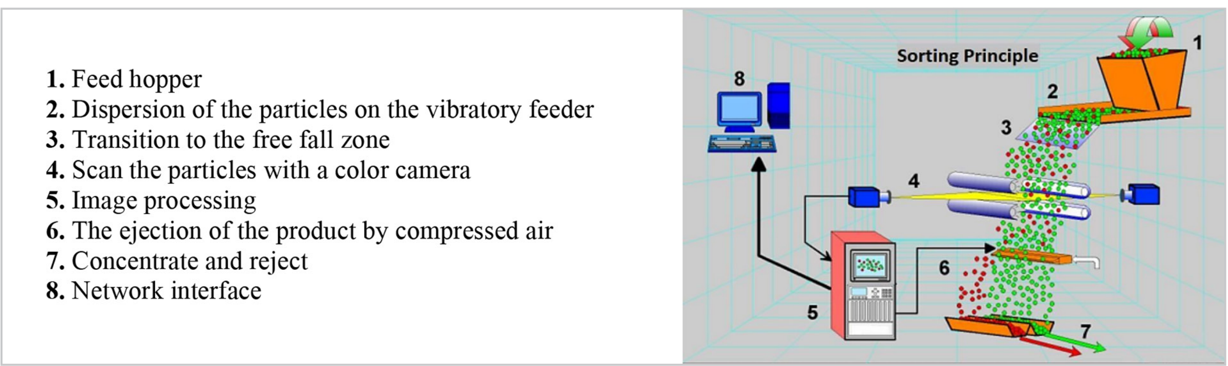

Figure 8 - Functional principle of the optical sorter (Von Ketelhodt and Vollmar, 2012).

To determine the RGB of mineral images to be separated we used the following Algorithm:

Begin
Load image (IMG)
Read red color of image (IMG) and save it in new image (RIMG)
Read green color of image (IMG) and save it in new image (GIMG)
Read blue color of image (IMG) and save it in new image (BIMG)
Calculate the mean of each image (MRIMG, MGIMG and MBIMG)
Showing all images (IMG, RIMG, GIMG, BIMG)
End

8. Results and discussions

Tests by Matlab codes were performed to determine the RGB of the several images from Boukhadra mining wastes; the results are given in the Table 7:

Table 7 - Determination of the RGB of images from the Boukhadra mining wastes.

Name	Limestone	Iron ore	Yellow marl	Gray marl
R	94-97	61-68	149-155	100-109
G	92-98	50-56	129-136	103-112
B	76-81	41-49	85-89	88-106

The scheme presented in Figure 9 is a proposed flow sheet for the management of the Boukhadra mining wastes.

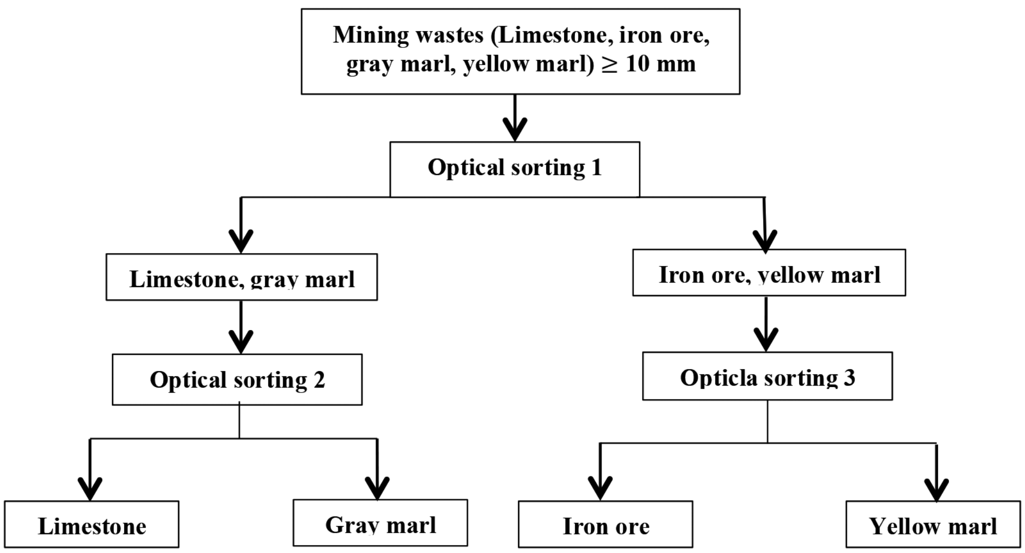

Figure 9 - Diagram of optical sorting for Boukhadra mining wastes.

For the management of optical sorter ejection system according to the RGB values, we use the following Algorithms:

For the management of optical sorter ejection system according to the RGB values, we use the following Algorithms:

Optical sorting 1
Begin
Load image (IMG)
Read red color of image (IMG) and save it in new image (RIMG)
Read green color of image (IMG) and save it in new image (GIMG)
Read blue color of image (IMG) and save it in new image (BIMG)
Calculate the mean of each image (MRIMG, MGIMG, and MBIMG)
The image is defined like this algorithm

If (the average of the red component (MRIMG) varies between 93 and 98 and the average of the green component (MGIMG) varies between 91 and 99 and the average of the blue component (MBIMG) varies between 75 and 82) Or (the average of the red component (MRIMG) varies between 99 and 110 and the average of the green component (MGIMG) varies between 102 and 113 and the average of the blue component (MBIMG) varies between 87 and 107) then
Showing that the image is ‘Limestone and Gray marl';
Call optical sorting 2

Else if (the average of the red component (MRIMG) varies between 60 and 69 and the average of the green component (MGIMG) varies between 49 and 57 and the average of the blue component (MBIMG) varies between 40 and 50) Or (the average of the red component (MRIMG) varies between 148 and 156 and the average of the green component (MGIMG) varies between 128 and 137 and the average of the blue component (MBIMG) varies between 84 and 90) then
Showing that the image is 'Iron and Yellow marl';
Call optical sorting 3

End
Showing the color of image (IMG)
End

Optical sorting 2
Begin
Load image (IMG)
Read red color of image (IMG) and save it in new image (RIMG)
Read green color of image (IMG) and save it in new image (GIMG)
Read blue color of image (IMG) and save it in new image (BIMG)
Calculate the mean of each image (MRIMG, MGIMG, and MBIMG)

If (the average of the red component (MRIMG) varies between 93 and 98 and the average of the green component (MGIMG) varies between 91 and 99 and the average of the blue component (MBIMG) varies between 75 and 82) then
Showing that the image is 'Limestone'

Else if (the average of the red component (MRIMG) varies between 99 and 110 and the average of the green component (MGIMG) varies between 102 and 113 and the average of the blue component
(MBIMG) varies between 87 and 107) then
Showing that the image is ' Gray marl';
End
End

Optical sorting 3
Begin
Load image (IMG)
Read red color of image (IMG) and save it in new image (RIMG)
Read green color of image (IMG) and save it in new image (GIMG)
Read blue color of image (IMG) and save it in new image (BIMG)
Calculate the mean of each image (MRIMG, MGIMG, and MBIMG)
If (the average of the red component (MRIMG) varies between 60 and 69 and the average of the green component (MGIMG) varies between 49 and 57 and the average of the blue component (MBIMG) varies between 40 and 50) then
Showing that the image is 'iron ';

Else if (the average of the red component (MRIMG) varies between 148 and 156 and the average of the green component (MGIMG) varies between 128 and 137 and the average of the blue component (MBIMG) varies between 84 and 90) then
Showing that the image is ' Yellow marl';
End
End

9. Benefits of the proposed method

Generally, sorting is an intermediate and indispensable step for waste treatment; its main purpose is to transform a group of mixed wastes into several categories easily recyclable. Similarly, mineral sorting is a proven technology in many industries around the world. It uses a variety of electronic sensors combined with high-speed processors that can be programmed to recognize certain characteristics of the ores: color, radiation, density, conductivity, magnetization, etc. A mechanical ejection system is then activated by the processor that ejects the particles from the feed (Murphy, Zyl and Domingo, 2012).

Moreover, optical and other sensor-based sorting techniques for materials have made rapid progress in Europe over the last 10 years (Wotruba, 2006). They are widely used in several mining industries other than phosphates to reduce wastes. Only one application in the phosphate industry was used by a phosphate mine in the early 1980's in western United States. Other phosphate extraction companies have recently shown interest in optical sorting and have conducted a prefeasibility test at the laboratory scale (Daoudi, Kukenska, 2013).

Therefore, the implementation of an optical separator in the mine site will have many benefits; this separation technique is fast, simple, malleable, economic and less polluted process (little dust because the particle size of minerals to be separated is ≥ 10 mm). It doesn't require large investments, and also saves travel expenses, loading, transport and treatment of mining wastes. Besides, it contributes to the selective sorting of different types of rock according to their chemical characteristic, which are composition and color (limestone, iron ore, gray marl and yellow marl). This will facilitate their recycling and reuse in the different sectors, (construction aggregates, cement, paint, ceramics , iron and steel, etc.).

To do this, the optical sorting of mining wastes from the Boukhadra mine makes it possible to dispose of unneeded materials (mine wastes), to free up the areas occupied by these latter and consequently to prevent environmental problems related to water and soil pollution following the leaching of mining wastes, dust, falling blocks to residents located downstream of the mine, etc.

10. Conclusions

The Boukhadra iron ore mine is operated by a combined method (open-pit and underground) which generates thousands of tons of mine wastes per year (waste rocks and others) that really causes major environmental problems: air, water or soil pollution, erosion and mine drainage, etc.

In order to assess their effects, representative samples of mine wastes, water and soil taken from the studied area reveal a contamination by dissolved iron due to the leaching of mining wastes.

To counter the phenomenon of mining drainage and avoid the erosion of mining wastes stored on the side of the mountain near the Boukhadra village residents, valorization of mining wastes can contribute to the reduction of stacked volumes by use of the optical technique.

Tests in color measurements show that there is a possibility for the management of the Boukhadra waste rocks based on color difference (RGB values of minerals).

Ore sorting technology is a less polluted process, which will contribute to the removal of the unneeded discharges and will also facilitate the recycling and the reuse of Boukhadra mining wastes.

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