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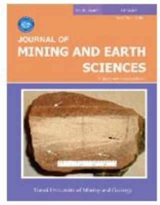

Short overview about iron ore beneficiation: a case study in recovering the iron ore from the tailing pond of the Kip-Tuoc processing plant

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ABSTRACT

Iron is a critical metal for many fields of life and industry. The iron-containing minerals are recovered from the iron run-of-mine (ROM) ore and the tailing pond (TP) of the previous processes. The minerals containing iron are hematite, magnetite, goethite, maghemite, etc. In addition, the invaluable minerals and gangue normally are quartz, kaolinite, gibbsite, pyrite, dolomite, chlorite, etc. Many methods to upgrade the iron content as well as separating the iron minerals and gangue are applied. Those technologies are magnetic separation, gravity separation, flotation, chemical separation, thermal beneficiation, or even the application of biotechnology. In Vietnam, there are many technological research projects on iron ore beneficiation and processing. The main technologies are washing and scrubbing methods, magnetizing roasting combined with a magnetic separator, spiral and magnetic separator, flotation, etc. The article shows a short review of the main methods in order to treat the type of raw material as well as some current applied technology in Vietnam. Based on the knowledge, a study to recover the iron of Kip-Tuoc tailing from the tailing pond is presented. The applied technology is the combination of a trommel screen, spiral and shaking table. The result showed that by applying the rational method and carefully controlling the operational parameters, the iron ore (from the tailing pond with 14.28% Fe) recovered up to 57.57% at the 59.49% Fe grade content. The iron content is suitable for feeding to the blast furnaces in Vietnam. Through the research results, a flowsheet for iron recovery at the tailing pond of the Kip Tuoc beneficiation plant is proposed and scaled up to industrial production's next step.

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1. Introduction

Iron is widely used in the life and defense industry. Currently, most iron ore mines are using unreasonable and outdated, asynchronous mining and mineral processing technology. This issue leads to waste, loss of resources, pollution and environmental degradation in many areas. With the current economic growth rate, most of the rich iron ore mines have been exhausted. So it is necessary to find appropriate technologies to efficiently process and exploit the poorer, more complex iron ore mines. The methods commonly used for iron ore upgrading in the world are gravity separation, magnetic separation and flotation. Currently, iron ore beneficiation plants in the world in general as well as in Vietnam particularly are mainly using gravity and magnetic separation technology. However because the iron ore is getting poorer, the content of strong magnetic minerals in iron ore is significantly low. With this type of ore, the method of magnetic separation is inefficient. The actual recovery degree of the entire process is approximately 80% at almost all companies in Vietnam. The rest amount of the iron is located in the waste rock and the tailing product. The most suitable separation method for poor iron ore (including the mainly weak magnetic and non-magnetic minerals), is gravity separation, flotation, or magnetization roasting - beneficiation. These methods allow obtaining a final concentrate with high iron content and increase the recovery degree. However, since the value of iron ore is not high, the above-mentioned solution is not used in practice (related to the relatively great production cost).

Iron-steel factories in Vietnam have been using a large amount of iron ore with high iron content (in fact, the iron concentrated ore feeding to the blast furnace usually has a grade content in the range of 58÷65% Fe). The amount of domestic iron ore is not enough for demand. Even, a large amount of the raw materials supplied to steel production factories must be imported. To supply the lowest production cost raw material (with suitable quality) to steel metallurgy as well as to improve the iron recovery degree from ore, the technology solution for rational recovery of iron minerals out of poor iron ores which are located at tailings ore dump is concerned and researched.

Kip Tuoc iron mine is located in Cam Duong commune, Lao Cai city, where there is an iron ore mining and processing plant of Minerals Joint Stock Company 3, Vinacomin - Minerals Holding Corporation. This plant was built and has started production since 2010. The current technological line of the Kip Tuoc process plant uses magnetic separation combined with gravity separation (on spiral equipment). The ROM ore has a content of 40.22% Fe. The magnetic minerals are recovered by a magnetic separator, and the product containing non-magnetic or weakly magnetic minerals is upgraded by spiral. The beneficiation efficiency of the plant is not high. The concentrate has an average recovery of 83.85% and a content of 61.05% Fe. The average content of tailings is approximately 14.28% Fe with an estimated volume of 500,000 tons. It can be seen that the amount of tailing ore after the beneficiation is relatively large. Furthermore, the iron content in the tailing ore is still quite high. The tailings product is currently stored in the waste area at Kip Tuoc. The issue related to wasting resources and polluting the environment is a risk if the tailing ore is not treated thoroughly. Therefore, it is necessary to study the technology to recover iron minerals from the tailings ore of the Kip Tuoc iron ore processing plant. From that, the optimal solution will be proposed. Furthermore, based on the research result, the second plant was invested in and operated in practice.

2. Short overview about the iron ore beneficiation

2.1. Introduction about iron ore

According to Morgan and Anders (1980), iron occupies a significant amount on the Earth. This issue explains the occurrence of iron minerals and iron deposits on the surface of the planet (Lu, 2022). The term “iron ore” is used only for iron-bearing deposits, which could be exploited and could be processed economically.

The minerals containing iron are hematite magnetite, goethite, maghemite, etc. In addition, the invaluable minerals and gangue normally are quartz, kaolinite, gibbsite, minnesotaite, berthierine, chamosite, orthoclase, albite, pyrite, pyrolusite, siderite, ankerite, dolomite, stilpnomelane, chlorite, etc. (Lu, 2022). However, the iron minerals generally are magnetite, hematite and goethite. The three types of minerals occupy up to 99% of the iron-bearing minerals in the world. Magnetite is a common mineral in iron ore deposits of metamorphic and magmatic origin, some of which are found in deposits of sedimentary origin. Magnetite is a highly magnetic and density mineral (Waychunas, 1991). Hematite is generally thought to form from the oxidation of magnetite (Morris, 1985; 1987; 2002). Goethite is an iron hydroxide oxide (α-FeOOH), which has the origin of sedimentation and metamorphism. Quartz is the most common gangue mineral in iron ore, while clay (kaolin and gibbsite) predominates in weathered ore deposits. Otherwise, they are minnesotaite and stilpnomelane. Moreover, the number of minority minerals that can go within the iron ore can be listed: minerals silicate (amphiboles, feldspars, and chlorites), carbonate (siderite, dolomite, and ankerite), sulfides (pyrite), and oxides (pyrolusite).

2.2. Iron ore processing technology in the world

2.2.1. Magnetic separation

Magnetic separation is the most effective method in order to treat iron ore. Generally, magnetic separation is the method using a magnetic field with the suitable intensity, gradient and other conditions to separate (which is based on the differences in magnetic susceptibility). The magnetic separation recovers normally the strong magnetic minerals, specifically here is magnetite mineral with a magnetic susceptibility of $625x10^{-6}÷1156x10^{-6}$ m^3/kg, 100 times higher than the magnetic susceptibility of the second-ranked martite mineral ($6x10^{-6}÷13.5x10^{-6}$ m^3/kg). For some types of equipment, production cost is low. The capacity can be up to 500 tons per hour of concentrate ore with very low operating costs (0.3÷0.5 kWh of electricity and 2 m^3 of recyclable water/ton concentrate ore). The magnetic separators are divided into two types: low-intensity magnetic separators (permanent magnetic drum separator, magnetic column separator, magnetic thickener and disk magnetic scavenger); high intensity and high gradient magnetic separators (Johnes wet high-intensity magnetic separator, Slon vertical ring and pulsating high gradient magnetic separator) (Lu, 2022; Xiong, 1998; 2006; 2008; 2010; 2012).

There are some typical flow sheets for upgrading iron ore using magnetic separators. In China, the 30.4%Fe ROM ore which contains magnetite and quartz, is prepared, ground, and separated into different particle sizes by ball mill, vibration screen, and cyclone. The magnetite mineral is recovered by multiple stages of low-intense magnetic drum machines. The result is the concentrate with 67.3% Fe and 37.1% of mass yield (Lu, 2022). The other flowsheet shows the combination of main technical equipment: ball mill, cyclone, magnetic column and drum LIMS. With the same types of ore, the technical criteria of concentrate ore are 68.4% Fe of grade, 34.8% of mass yield. The iron recovery achieved 81.7%. Furthermore, drum LIMD can be combined with the magnetic thickener, disc magnetic scavenger and reverse flotation in order to treat the magnetic ore.

For oxidized iron ores, those types are much more difficult to separate due to the low magnetic susceptibilities. Nevertheless, the high intensity and high gradient magnetic separator can solve relatively successful this problem relatively successfully. One of the flowsheets to apply in this situation is the combination of Drum LIMS and Slon magnetic separators. For one of the case studies, the oxidized ore containing about 50% Fe is upgraded to the concentrate containing 64.6% Fe with the iron recovery ratio of 88.0%. The Slon magnetic separator shows superiority in order to treat the oxidized iron ore. Some flowsheets also show the combination of this equipment with reverse flotation, drum LIMS (low-intensity magnetic separator), MIMS (middle-intensity magnetic separator), spiral separator, and centrifugal separator as mentioned by (Lu, 2022) in his books.

2.2.2. Gravity separation

This method is used mainly for hematite/goethite iron ore. They normally need to extend processing at their source (mine) before transportation. The purpose is to supply a higher quality of iron (reduce undesirable elements like

Si and Al) with a suitable particle size (6.3÷31.5 mm) for the market. Miller (2013) summarized the technology to treat non-magnetic ore developed through four generations involving dense medium separation, jigs, spiring, washing and desliming, and even more scrubbing.

For dense medium separation, some well-known companies that are utilized in South Africa, Australia. This method is the best solution for gravity separation. The medium for this solution is ferrosilicon.

Jigging is the oldest form of mineral separation, it is still widely used in iron ore. This equipment is particularly applied for low-grade iron ore, which has the amount of Fe content reach approximately saleable product. The case study can be shown in South Africa. Following that, the (50÷60% Fe) ROM ore can be upgraded to the customer's demand of 64% Fe. These activities contribute to the enhancement of the source of the mine (Pretorius and Hoffmann, 2006; Stanton and Bannear, 2013).

The upflow classification is normally combined with the spiral, hydrocyclone in order to treat fine goethite/quartz composite particles and de-fine clay slimes. For spiral, this equipment is normally used to de-slime iron ore fines below 1mm. The researches of Clout (2013), Selvapandian and Barr (2013) also demonstrated this opinion. In order to improve the overall grade and recovery, magnetic separation is combined with a spiral at almost flowsheet. The case study can be listed in Canada's Labrador Province (with the ore containing hematite) (Sherrell and Nevens, 2010).

There were many solutions and research using gravity separators to recover iron from ore as presented above. However, no research mentions using a shaking table to treat the fine and ultra-fine particle-size iron ore, although the great advantage of this type of equipment is the high accuracy separation following the gravimetric density as well as the low-cost investment and production. This issue needs further research furthermore next time.

2.2.3. Flotation

Forth flotation is an effective method to remove impurities from iron ore. The purpose of iron ore treatment using flotation is the separation of silica out of valuable minerals, aluminum removal, sulfur removal, and phosphorus removal.

For silica removal, there are three flotation processes for the type of iron ore. They are direct flotation, reverse cationic flotation and reverse anionic flotation. While direct flotation is rarely applied in practice, reverse cationic flotation is generally applied in the iron ore industry in America, Canada, Brazil, India, Sweden, and Australia (Iwasaki, 1983; 1999; Nummela and Iwasaki, 1986; Uwadiale, 1992; Ma et al., 2011). Meanwhile, China is a country, which prefers applying reverse anionic flotation (Filippov et al., 2014; Nakhaei and Irannajad, 2018; Zhang, et al., 2021). Moreover, reverse cation flotation technology is being more and more used in the world. However, this technology requires de-slimes before treatment. This is the main cause of fine-grained iron loss. Reverse flotation using an anion collector is the process of removing quartz from iron ore. The advantage of this flotation technology is that it has less effect on slime and the dosage range of the collector is much less (Zhang, et al., 2021). Following that, reagents also present a diversity of types of with collectors (mono and diamines, oleic acid, tall oil, fatty acid soaps or a combination of the anion and cation collectors), depressant (starches), frother (MIBC, pine oil), activator, dispersant, and flocculants (Quast, 2017; Rath and Sahoo, 2020). The practice of flotation applied in silica removal can be listed in some notable cases at Tilden Mine (USA) (Colombo, 1986; Houot, 1983; Nummela and Iwasaki, 1986; Yang, 1988). In the USA, iron ores are finely disseminated and intimately associated with the gangue. So it requires very fine grinding to liberate valuable minerals from non-valued minerals. The problem of entrainment of fine slime particles is solved by selective flocculation before using reverse cation flotation. In China, iron ore enrichment begins with the direct flotation of iron oxides using anionic collectors or reverse cation flotation. At present, the trend is reverse anion flotation to reduce the dosage range of the reagent and to reduce the significant loss of iron during the de-slimes phase (Ma, 2012). In Brazil, reverse flotation using cation collectors is used the most. There is no de-slime phase and the collector used is the ether amine; the pH of the flotation medium was about 10.5 and the depressant was corn starch (Lu, 2022). Vieira and Peres (2007) suggested that, when using ethers monoamine, the quartz flotation efficiency decreased rapidly for particles coarser than 150 microns.

For aluminum removal, reverse cationic flotation also is used to separate a part of aluminum in kaolinite but the efficiency is not high. The research on this issue is still limited. The mechanism of kaolinite flotation has not been understood deeply. Paradip et al. (1993) tried to study the flotation of types of Indian iron ore with the content of Al up to 11.6%. The concentrated ore after flotation has 60% Fe of content and the amount of Al is reduced to 4.7%. In Australia, there is also some research about kaolinite flotation, which is contained in some iron ore. The purpose is to know the way to recover Fe and remove as much as possible the amount of Al. Aluminium also is contained in gibbsite minerals. Compared to kaolinite, the separation of gibbsite out of hematite/magnetite ore is extremely difficult due to the similar surface characteristics. Research on this issue needs to continue next time.

For the next element needing removal, phosphorus is an extremely un-valuable mineral for iron ore because the presence of P leads to the increasing brittle of steel. In case phosphorous belongs to a specific mineral (normally in apatite), flotation can be applied for the handle. The collector is fatty acid while the dispersant is sodium silicate at pH 8.5÷9 (Su et al., 1998). The process can be achieved easily. But the problem that needs to be solved is the optimization of collector dosage, which (if too much) could be effect negative for the subsequent pellet stage. The LKAB concentrator in Kiruna, Sweden has treated the iron ore with 1%P (which exists in the apatite). The result is reported positively. Phosphorus has also existed in goethite (Graham, 1973; Powmceby et al., 2019). This form is difficult to separate by flotation or whatever other physical separation.

The sulfur typically exists in pyrrhotite and pyrite of magnetite ore, which is easily removed by magnetic separation. In some cases, flotation also is applied to separate pyrrhotite from iron ore. The reverse flotation process is a good solution to float pyrrhotite from the magnetite in the Marcona Mine in Peru (Cline and Rosas, 1975; Iwasaki, 1999). There were only notes about this solution that the type of mill should not a carbon - steel due to the chemical interaction (leading to the oxidation of the pyrrhotite) (Cline and Rosas, 1975).

2.2.4. Other methods used for iron ore separation

The other methods of separation can be listed: chemical separation, thermal beneficiation, or even the application of biotechnology. For the first special method, the chemical reaction is applied to solve some elements like phosphorus, sulfide, or aluminum in iron ore, which can not be removed by solution as mentioned above. Thermal beneficiation is developed to treat the complexity of deposits. The purpose is an achieve the Fe grade at a high Fe recovery. Magnetic separation separates excellent strong magnetic minerals like magnetite. However, almost iron ore is dominated by hematite, goethite, and even siderite which has weak magnetic characteristics. The method uses thermal to transform their characteristics into high magnetic susceptibility minerals. The solution is "low-temperature magnetizing roasting" or "high-temperature deep reduction roasting". After this process, ferromagnetic can be separated by magnetic separators. The latter method is biotechnology. The mechanism of this method is the microorganisms adhere and change mineral surfaces. From that, other processes like flotation or flocculation process can be used to recover valuable elements. Both three methods are less applied in practice due to the low feasibility of the method and the low-efficiency economy.

2.3. Research on iron ore beneficiation in Vietnam

In Vietnam, there have been many research reports on iron ore beneficiation, such as limonite ore separation at Tien Bo mine - Thai Nguyen, laterite iron ore processing in the Central Highlands, diluvial iron ore separation in Quy Xa mine - Lao Cai, iron ore separation at Ha Tinh, Ha Giang, Cao Bang, etc.

For the research on the separation of iron ore limonite in the Tien Bo mine, the ROM iron ore has a content of 39.85% Fe. The beneficiation process is the combination of washing and scrubbing methods (vibration screen, mechanical classifier, and trommel screen) and reduction roasting. The concentrated ore after washing has 49.10% Fe at a recovery of 76.32%. The quality of this product is upgraded by the subsequent deep process to 55.80% Fe of content. The flowsheet of this type of iron ore is indicated in Figure 1 (Vu, 2002).

In the case of laterite iron ore in the Central Highlands, the 29.91% Fe ROM ore is upgraded to the concentrated ore with 46.26% Fe of content at the recovery of 69.80%. The use of technology is similar to the case study of the Tien Bo mine mentioned above. The difference is the reduction roasting stage is replaced by magnetizing roasting combined with a magnetic separator (Tran, 2013). Another method for this kind of ore is flotation. The positive result is indicated with the value of 51.05% of Fe content but the recovery is quite low with 30.61%.

In 2007, the National Institute of Mining - Metallurgy Science and Technology carried out the project "Research on the selection of iron ore beneficiation technology at Ha Tinh small mines. The technological flowsheet includes the process of washing and scrubbing (the main part), following is the stage of magnetizing roasting - magnetic separation. As a result, the concentration is 59.83% Fe of grade content at the actual recovery of 87.88% (Nguyen, 2007a). With the same project, Nguyen (2007b) has also presented research on upgrading the concentrated ore after washing by flotation. The feeding ore with 48.03% Fe is upgraded to 52.64% at the recovery of 85.49%.

The Vietnam Association for Mineral Processing has researched the beneficiation method for some poor iron ore samples in Ha Giang. The two magnetite iron ore samples, named ST1 and ST2 have contents of 48.38% Fe and 52.94% Fe, respectively. The reasonable technology for these ores is two-stage crushing, gravity separation in combination with magnetic separation. The concentrated ore obtained has a grade >63% Fe and a recovery of 73÷75% (Nguyen et al., 2009).

In 2014, the National Institute of Mining - Metallurgy Science and Technology - proposed a researched flowsheet for diluvial iron ore separation from Quy Xa mine - Lao Cai (Figure 2). The flowsheet shows the washing solution for coarse-grained washing, magnetic separation, and magnetizing roasting - magnetic separation for fine particle size ore. The equipment used in the washing process is the trommel screen/the screw ore washer combined with the mechanical classifier. The ROM ore composition is mainly goethite 60÷62%, hematite 11÷13%, the remaining components are gibbsite 2÷4%, quartz 4÷6%, feldspar 3÷5%, illite 4÷6%, kaolinite + chlorite 4÷6%, talc 1÷3%. The total Fe content is 47.11%, accompanying impurities such as Al_2O_3:

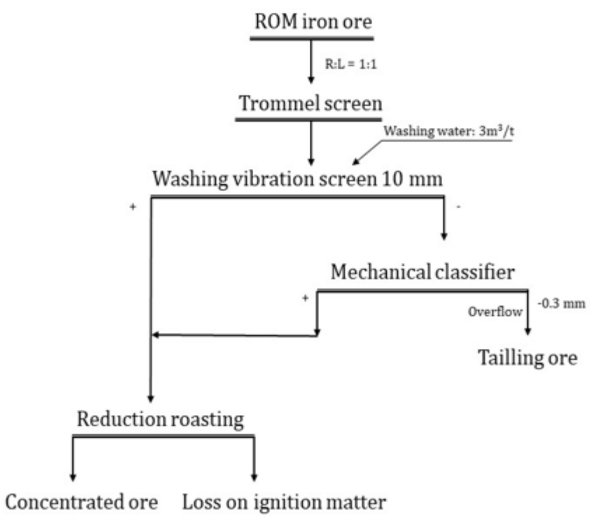

Figure 1. Flowsheet of Limonite ore separation at Tien Bo mine - Thai Nguyen (Vu, 2002).

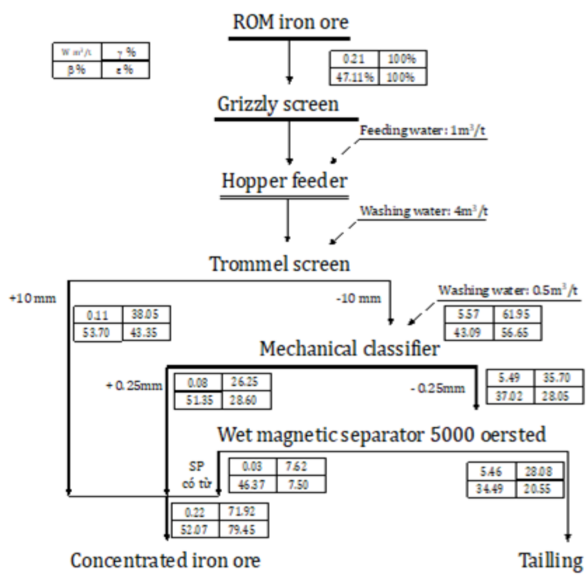

Figure 2. Proposed flowsheet for deluvi iron ore separation from Quy Xa mine - Lao Cai (Pham, 2014).

5.41%; MnO: 2.80%; SiO_2: 4.28%; S: 0.10%. The result obtained from the separation process is that the total Fe concentrate has a content of > 52% at the actual Fe recovery is ~ 80% (Pham, 2014).

Pham et al. (2017) studied the technology to recover Fe from the tailing of Ban Luoc iron ore, Cao Bang by the magnetizing roast-magnetic separation. The two samples used have the main mineral compositions of goethite, hematite and clay with an iron content of 29.84% and 35.5%. Iron ore concentrate has a content of 57÷58% at a recovery of 78%.

For the weathered iron ore, a sample from Na To mine, Xieng Khouang, Laos is researched. The minerals composition are hematite, limonite, magnetite, quarzt, fenspar, clay, etc. The iron content of ROM ore is approximately 23.58%. The amount of fine material below 0.045 mm accounts for 32.24% while iron exists mainly in coarse particles. The research shows the solution with the combination of the washing process, gravity separation, magnetic separation, and magnetizing roasting - magnetic separation. The result shows the concentrated ore with 60.19% Fe content at the recovery of the final stage 86.95% (Nguyen, 2016).

For the the case study as will be mentioned in this article: Kip Tuoc Iron Mine belongs to the Minerals 3 Joint Stock Company - Vimico, which is located in Cam Duong Commune, Lao Cai City. The activities of iron ore mining and processing have been conducted here since 2010. This type of ore is derived from metamorphic sediments, ores are of the quacsite - magnetite and hematite types. Through the results of mineral composition analysis, the iron ore minerals are mainly hematite and magnetite. The main rock mineral is quartz. The accompanying mineral is feldspar. The original ore has an average iron content of 53% with the characteristics of the three ore bodies generally having little difference. Iron ore is dark gray with hematite content from (7÷8%) to 65% (individually up to 75%) and magnetite from 1÷63%. The quantity between hematite and magnetite is inversely proportional to the slope. Non-ore is mainly quartz and some other minerals accompanied. There is also chalcopyrite, but not much. The content of accompanying elements: SiO_2: 14.62%, S: 0.08%, P: 0.053%. The rock surrounding the ore is the greisenized quartz-muscovite schist of the Sin Quyen Formation and the greisenized aplite granite of the Song Chay Complex (IMSAT, 2009). The beneficiation plant has been built and put into production since 2010. The current technological line is a combination of the stages of crushing (jaw, cone crusher) - grinding (ball mill) - classification (mechanical classifier); magnetic separation (drum low-intense magnetic separator) combined with gravity separation (spiral). The ROM ore has a content of 40.22% Fe. The strong-magnetic minerals are recovered by magnetic separator, and non-ferromagnetic /weakly magnetic minerals are separated from the gangue by spiral. The efficiency separation of the plant is not impressive. The average recovery of the whole production line is only 83.85% at the content of concentrated ore is 61.05% Fe. The average content of tailings ore is up to 14.28% Fe with the estimated volume currently about 500,000 tons (VIMICO, 2022). The current technological flowsheet of the Kip Tuoc iron ore processing plant is indicated in Figure 3. The production result of the plant is shown in Figure 4.

As mentioned above, the amount of tailing ore as well as the iron content after the processing is relatively high. This amount of material, after natural drying in the outside reservoir, is completely dumped into the TP outside the Southeast area adjacent to the eastern end of the excavation area. The tailing ore is disposed of by trucks, excavators and bulldozers. This amount of material is the main object of research technology and investing in new equipment to recover more iron minerals. Thereby, the result leads to improving the actual total yield and recovery degree of the processing plant. In addition, the appropriate treatment of this ore will contribute to avoiding the waste of resources and minimizing environmental pollution. The next part of the paper also presents this case study. Figure 5 shows some pictures of the tailing ore TP at the Kip Tuoc iron processing plant.

Overall, the solution in study activities focuses on washing and magnetic separation, magnetizing roasting - magnetic separation, and flotation. However, gravity separation is carried out increased gradually in practical production.

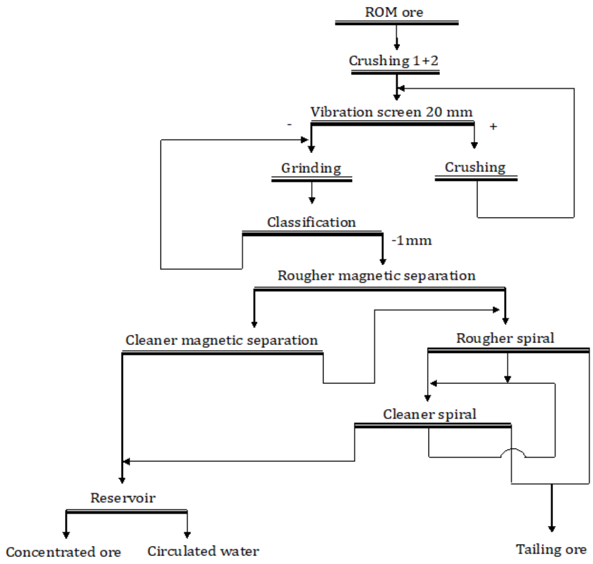

Figure 3. The flowsheet of Kip Tuoc iron ore processing plant (IMSAT, 2009).

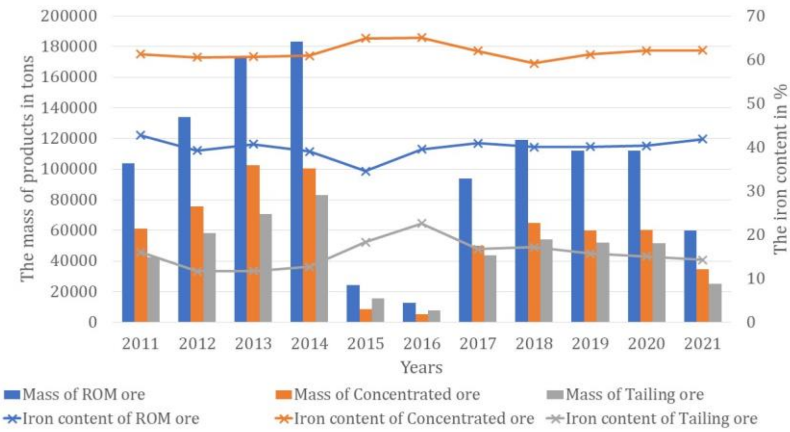

Figure 4. The output technological criteria of the Kip Tuoc iron ore processing plant annual years (VIMICO, 2022).

Figure 5. Images for the waste dump of Kip Tuoc iron ore processing plant.

The specific equipment is spiral. Meanwhile, the shaking table with the advantage of high accuracy separation is not researched and applied in production. The purpose of this paper is to introduce a case study using a combination of these kinds of equipment.

3. Results and discussions in the case study of tailing samples in the Kip Tuoc tailing pond

3.1. Research methodology

In this paper, there are four types of research methodology, which are implemented. The first one is the literature review, which is necessary for the overview of the iron ore processing part. The result of the method not only gives information about the current technology but also gives the direction for the specific object (tailing ore of the Kip Tuoc iron ore processing plant). The field trip method and laboratory-experiment method are used for tailing ore sampling; currently production line assessment as well as the appropriate technology chosen for this type of material. In order to define the characteristics and properties of feed ore as well as the products after treatment, the sieving analysis method, X-ray diffraction; atomic absorption spectroscopy (AAS), inductively coupled plasma atomic emission spectroscopy (ICP-AES); scanning electron microscope - SEM analysis are used.

3.2. Tailing ore sample characteristic

After sampling and handling samples, the sample is defined the particle size distribution, chemical composition, and mineralogical composition. The particle size distribution of samples is analyzed by wet sieving analysis, the grade content of each range size fraction was tested by ICP-AES and AAS. The result is shown in another publication (Pham et al., 2023).

It can be seen in Figure 6 that the small particles and fine particles account for a significant amount. While the mass of over 2 mm particles occupies 1.14% with 14% Fe content, that of below 2 mm material has a yield of up to 98.86% with 14.28% Fe content. Although the Fe content is similar, the particle size distribution of the part +2 mm is not uniform and wide. Moreover, the Fe distribution in this range size is low. Those issues lead to technical obstacles in the separation of this particle size, as well as not economic efficiency. Therefore, these coarse particles can be disposed of directly during the screening stage without beneficiation. The iron distribution is mainly focused on the grain size below 0.5 mm with a content up to over 96%. The large amount of Fe belonging to this range size can be explained by the low-efficiency separation of the magnetic separator and the presence of hematite minerals in the ore. The amount of particle size 0.5÷2 mm is relatively small, about 3%. This part can be treated with a part below 0.5 mm with the same technology. From that, the average recovery of the production line will be increased. Since this material is the tailing ore and low value, the gravity separation (spiral, shaking table) solution with the low operation and investment cost is mentioned and oriented.

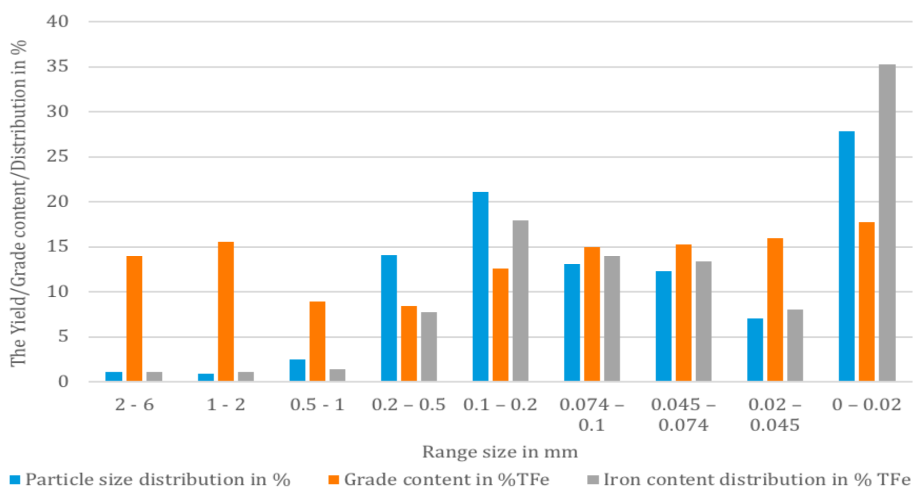

Figure 6. The particle size and the iron content distribution of sample.

The iron content in the sample is pretty low because it is the tailings ore of the Kip Tuoc iron ore processing plant. Except for iron, there are no other economically valuable minerals and elements. The best solution for this type of material is focused on maximum iron recovery technology.

The Kip Tuoc iron tailing ore belongs to original ores with low iron content. Iron minerals are ferromagnetic minerals and weak magnetic minerals, with high gravimetric density. The gangue is mainly of silicate minerals with low density. The iron distribution is focused on the particle size below 0.5 mm. When combining this amount with the material belonging to two narrow range sizes of 0.5÷1 mm and 1÷2 mm, the Fe distribution of particle size below 2 mm is up to 98.86%. The large particles have a cubic, irregular particle shape. The small particulate is mostly flattened in shape. The degree of difference in size is not too great. The mass of oversized particles is there but not much. The heavy minerals composition only contains iron oxide minerals (hematite, magnetite). This is convenient for the orientation of quality improvement by gravity separation, in particular using the spiral and the shaking table.

3.3. Experimental result in tailing processing by gravity separation

The test was conducted in some gravity separator. The reason for the choices of trommel screen, spiral, and shaking table is the low investment and operation cost. The solution is appropriate for this type of poor ore, which has a low economic value. The optimal test condition and results of above mentioned three stages are shown in Tables 1÷4.

Table 1. The optimal test condition.

Stages	Trommel screen	Spiral	Shaking table
Optimal study condition	- Rotating speed: 35 RPM; - Liquid/Solid ratio: 5; - Pressure washing (water): 2 atm; - Feed rate: 6 m^3/h.	- Solid concentration: 25%; - Flow rate of feed slurry: 3 m^3/h.	- Frequency: 1.67 Hz; - Amplitude: 10 mm; - Feed rate: 0.3 kg/minute; - Loading water: 0.6 liters/minute; - Washing water: 1.2 liters/minute; - Inclined bed surface: 1.5 degrees.

Table 2. The optimal experimental result in the trommel screen stage.

Sample	Iron content,% Fe	Yield,%	Recovery,%
Feed ore (tailing ore at TP)	14.28	100.0	100.00
I. Oversize product	11.12	2.47	1.92
1. Over 2 mm	*13.78*	*1.06*	*1.02*
2. Below 2 mm	*9.12*	*1.41*	*0.9*
II. Undersize product	14.36	97.53	98.08

Table 3. The optimal experimental result in the spiral stage.

Sample	Iron content,% Fe	Yield,%	Recovery,%
Feed ore (“below 2 mm” product)	14.36	100.00	100.00
Concentrate after spiral	15.06	85.41	89.51
Tailing after spiral	10.33	14.59	10.49

Table 4. The optimal experimental result in the shaking table stage.

Sample	Iron content,% Fe	Yield,%	Recovery,%	Silicate,%Si
Feed ore (concentrate after spiral)	15.06	100.00	100.00	-
Concentrate after shaking table	59.41	16.78	66.15	12.00
Tailing after shaking table	6.13	83.22	33.85	-

It can be seen that after the shaking table stage, the concentrate has 58.00% iron content with 12% content Si. The product is suitable for the demand of the customer as well as acceptable for iron-steel metallurgy.

In the particular final stage, the yield of concentrated product is 22.17% at an iron recovery of 64.29%. For the whole three stages, that recovery value in total is 10.86% at the iron recovery of 45.00%. For the aim of re-processing and recycling iron from the tailing ore of waste dump, the result can be accepted. From that, one of the best flowsheets is suggested for the case study, which is shown in Figure 7. The result for the whole process according the Figure 7, is shown in Table 5.

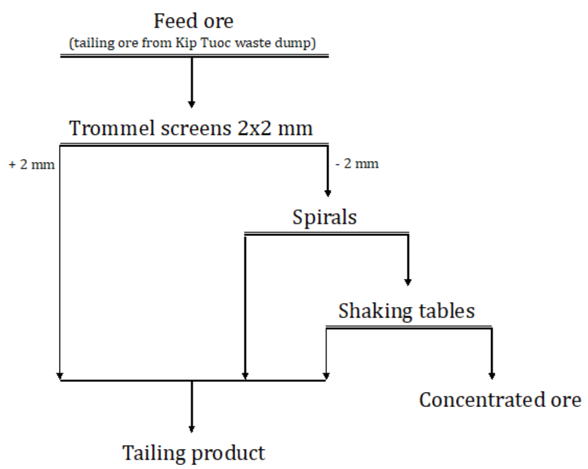

Figure 7. Proposed flowsheet for iron recovery from the tailing ore of Kip Tuoc.

Table 5. The result of re-process according to the proposed flowsheet.

Product	Iron content, % Fe	Yield, %	Recovery, %
1. Oversize product after trommel screen stage	*10.7*	*2.56*	*1.92*
2. Tailing after spiral	*10.56*	*14.58*	*10.78*
3. Tailing after shaking table stage stage	*6.15*	*69.04*	*29.73*
Total tailing	7.03	86.18	42.43
Concentrate	59.49	13.82	57.57
Feed ore (from TP)	14.28	100	100

4. Conclusions

Iron is the most critical material for the life and defense industries. Iron has recovered from iron ore with the popular minerals hematite, magnetite, goethite, etc. Besides that, the tailing iron ore, which is the product of the previous low-efficiency process, needs re-processing and recovering.

The paper presents a review of the main methods to upgrade the iron content as well as separate iron minerals out of the gangue. It can be seen that magnetic separation, gravity separation, and flotation are used most.

Based on the literature review, the paper also shows the case study of upgrading the tailing ore of the Kip Tuoc iron ore processing plant. By using the combination of the trommel screen, spiral, and shaking table, the iron grade content increased to 59.49% at a recovery ratio of 57.57%. The tailing after re-processing has 7.03% Fe content. The case study also defines the optimal parameters for each stage at the lab scale. Those are the important basics for scale-up in the future as well as the reference for the iron tailing processing at other tailing ponds in Vietnam and around the world.

Further work should be the strict control of the technology to improve the efficiency recovery.

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Contributions of authors

Hai Thanh Pham - wrote the article, discussed the problem, created the idea, experimented, and prepared the pictures and database; Dung Kim Thi Nhu - designed ideas and checked the manuscript; Luan Van Pham - has a role in experimental design, test conducting, and data analysis; Nhung Thi Pham, Chinh Thi Vu - experimented in the laboratory; Toi Trung Tran - analyzed samples and discussed the problem; Thinh Van Tran - organized the field trip, documents, and sample supplies.

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