Heliyon 10 (2024) e31986

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of roasting process on the V (anti-tumor agent) recovery from the slag of the electric arc furnace (EAF)

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ARTICLE INFO

Keywords:
V extraction
Anti-tumor particles
Optimization process
Salt roasting
Na_2CO_3

ABSTRACT

Due to the lack of mineral sources of Vanadium (V) in many parts of the world and its recent applications in the field of medicine (as an anti-tumor agent), one of the biggest sources of V is the extraction of V as V_2O_5 from steel slag in melting process. In this study, the pyro-hydrometallurgical process has been investigated for the extraction of V from steel slag created in a convertor. To get an optimum process of salt roasting, the effect of roasting temperature, time, salt value, slag particle size, and cooling method have been investigated. For this purpose, slag samples were roasted with sodium carbonate and then dissolved in water. The amount of V_2O_5 obtained by optical spectrometry is the efficiency criterion of this process. Results showed that the optimum condition for the extraction of V_2O_5 from steel slag was 15 wt % of Na_2CO_3 as a salt roasting agent and hating for 60 min at 1100 °C.

Nomenclature			
EAF	Electric Arc Furnace	mm	Millimeter
V	Vanadium	Wt.	Weight
h	Hour	g	Gram
°C	Degree of Celsius	ppm	Part Per Million
min	Minutes	m	Meter
XRD	X-Ray diffraction analysis	Na	Sodium
SEM	Scanning electron microscopy	O	Oxygen
LOI	Loss on Ignition	C	Carbon

1. Introduction

Some metals can be used in different fields due to their unique properties [1–3]. Vanadium (V) is an essential element with a burgeoning significance, particularly in the medical domain, where it demonstrates promise as an anti-tumor agent [4,5]. Recent advancements in medical informatics have highlighted the potential of V compounds in combating various forms of cancer, sparking

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https://doi.org/10.1016/j.heliyon.2024.e31986
Received 19 February 2024; Received in revised form 24 May 2024; Accepted 27 May 2024

interest in novel extraction methods to meet the growing demand for this critical element [6]. However, the scarcity of natural mineral sources of V in many regions necessitates innovative approaches for its extraction. One such avenue lies in the utilization of steel slag, a byproduct of steel manufacturing processes, as a reservoir of V. The mechanism of V compounds in cancer treatment involves their ability to induce apoptosis (programmed cell death) in cancer cells while sparing healthy cells [7,8]. Additionally, V compounds have been shown to inhibit angiogenesis (the formation of new blood vessels) in tumors, thereby impeding their growth and metastasis [9,10]. Furthermore, V-based drugs have exhibited potential in modulating cellular signaling pathways involved in cancer progression, including the PI3K/Akt/mTOR pathway [11–13]. The optimization and analysis methods were used in different industrial applications [14–16]. The extraction of V from steel slag involves a multi-step and optimized process, with salt roasting emerging as a crucial technique. Salt roasting, employing agents such as sodium carbonate (Na2CO3), presents an efficient means of liberating V from its matrix within the slag. Optimal conditions for this process entail a delicate balance of parameters including roasting temperature, duration, salt concentration, and slag particle size, alongside considerations regarding cooling methodologies. Drawing insights from recent advancements in related fields, this study aims to elucidate the intricate dynamics governing the roasting process and its impact on V recovery efficiency. By synthesizing principles from hydrometallurgical process, materials science [17,18], and medical informatics [19–21], this research endeavors to optimize the salt roasting procedure, thereby maximizing V yield from steel slag. In addition, nowadays there is a growing need of V to use in other industries such as transportation, vessels, steel making (more than 98 %), non-ferrous alloys, chemical productions and electrical batteries. V increases the toughness and strength of steel products as an additive in steel making process. Usually, V is used as a catalyst for the production of sulfuric acid in chemical industries. The V grade is very low about less than 1 % of common grade from V ores for direct extraction of V from mine, [22–25]. As mentioned before as an additive material, approximately more than 80 % of the usage of V is for increasing the strength of steel in steel making process [24–27]. Due to the lack of primary source of V in the nature, the amount of industrial wastes such as steel slag may become an environmental problem. So, processing of slag as a solid waste material always is an essential purpose in environmental protections. Always steel making slags as a wide group of secondary raw materials are one of the greatest interest for the extraction of V. Usually V oxides turn to a part of steel slag during the purifying of steel in furnace [27–29]. During the steel making process, there are five types of slag. Ladle slag (LF), blast furnace slag (Ironmaking slag), basic oxygen furnace (BOF) slag, steel furnace slag (SF) and electric arc furnace (EAF) slag. Usually EAF furnace is used for the production of high quality steels. During these recent years, there are a few investigations supported to extract V from the steel slag and were focused on roasting process for the extraction of V [30–33]. The V

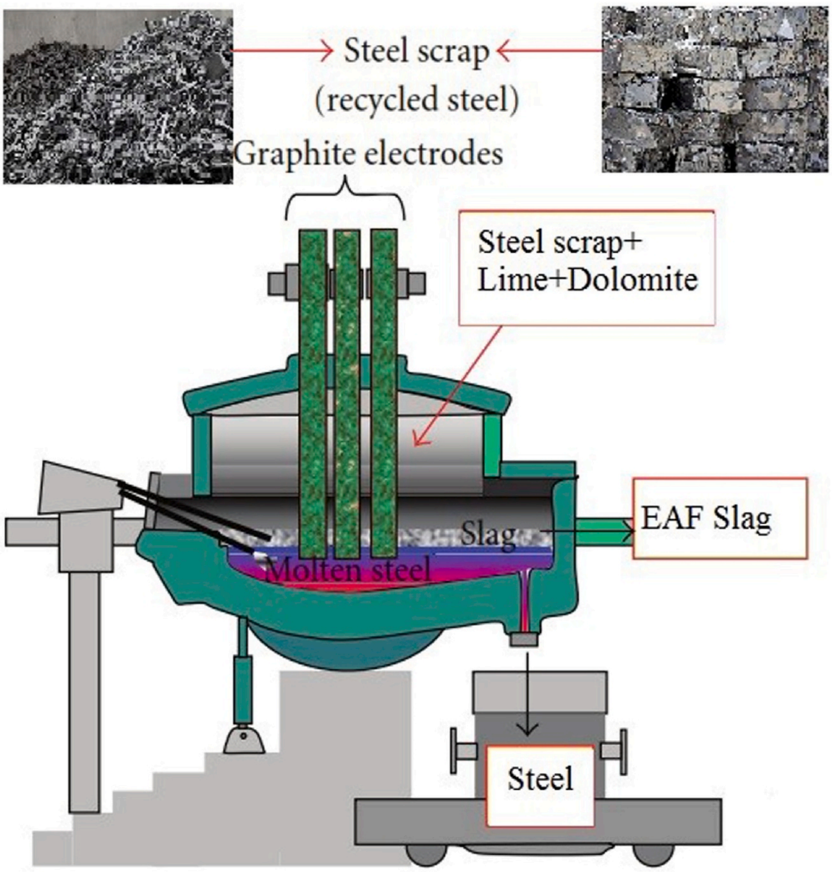

Fig. 1. The schematic drawing of EAF steelmaking process.

extraction method is classified in two branches: hydrometallurgical and pyro – hydrometallurgical. Hydrometallurgical method is classified in two acidic and alkaline groups. Usually the V mineral compositions cannot be solved in industrial acids due to their low solubility. In alkaline solving process, the extraction conditions are generated by solving the V compositions in primary material in an alkaline solution. Among many suggestions for this purpose, the most applied one is alkaline roasting with salt (NaCl) or Na_2CO_3 [32–34]. Due to the production of high amount of impurities during the acid leaching of V from the steel slag, sodium bicarbonate and sodium carbonate are used for the recovery of V from roasted steel slag [31,35–37].

In this study, a new process has been proposed to extract V from steel slags bearing in EAF furnaces. According to this investigation, Na_2CO_3 roasting process has been optimized for the extraction of V in the most efficient state.

2. Experimental procedure

2.1. Materials and methods

The steel slag begins to be melted with the aims of electric arc when passing the electrical current through graphite electrodes. Fig. 1 shows the steel making process and slags during the process in EAF furnace of steel companies in Iran. According to Fig. 2, after grinding the slag samples in a circular container with aluminum balls for 2 h, the slag agglomerations with a mass of 5 g were attained by adding water on them.

Then, Na_2CO_3 powder was used to roast slag samples. On the other words, using of sodium carbonate leads to generation of less polluting and harming to environment [27,31]. An electric muffle furnace was used to roast the slag sample after mixing and pelletizing certain values of Na_2CO_3 powder. The output of pelletizing process are pellets in sizes of 4∼25 mm. The effect of roasting time and temperature was investigated versus the roasting experiment and different sodium carbonate ratios. The optimization process was done in two stages. In the first stage, the effects of mesh size, roasting time and temperature have been investigated and then, roasting parameters have been optimized. The phase of samples and the V amount were determined using the X ray diffraction and spectrophotometry methods, respectively.

2.2. Slag properties

Usually slag particles produced in EAF have angular in round shapes. The distinct sharp edges of these pebbles are shown in Fig. 3 (a–f) in different scales of (a) 500 μm, (b) 200 μm, (c) 50 μm, (d) 20 μm, (e) 10 μm, and (f) 5 μm. Most broad particles have irregular spherical shapes with sharp edges. These sand sized slags are cylindrical and rounded at an angle with a porous structure. As can be seen in Fig. 3, very rough and porous surface textures with a porous structure can be observed.

Fig. 4 and Table 1 illustrate the chemical composition of the slag sample using X-ray diffraction test. According to Table 1, the main phase in the EAF slag is CaO. Usually the free CaO in this composition reacts with water and converts to $Ca(OH)_2$ [33]. The base of this kind of steel slag is CaO with a high value percentage. So, hydrometallurgical process during the roasting leads to generation of calcium vanadate which is insoluble in water. But, this is not applicable in this approach. On the other words, it is necessary to use a roasting process using an alkaline salt such as Na_2CO_3 to produce V_2O_5.

3. Results and discussion

3.1. Selection of slag mesh size

Fig. 5 shows slag particle size on the roasting efficiency with Na_2CO_3 as roasting salt for 90 min at 900 °C. As can be seen in Fig. 5, there isn't considerable change of the roasting efficiency vs slag mesh size. This means that diffusion phenomenon hasn't enough effect

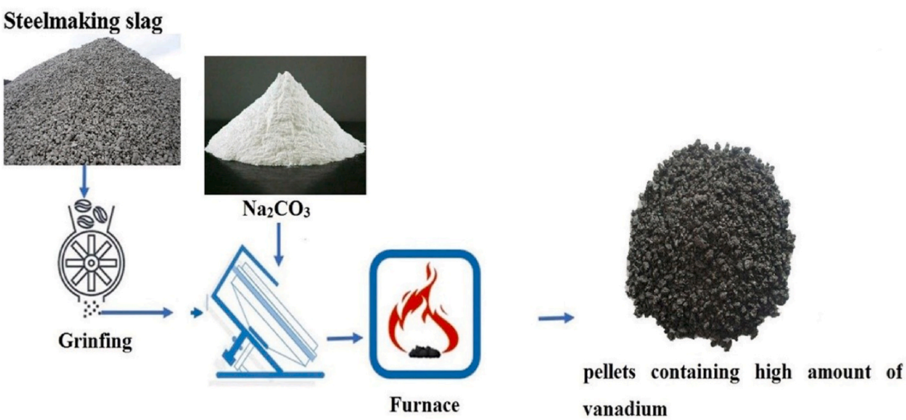

Fig. 2. Extraction process of V from the steel slag.

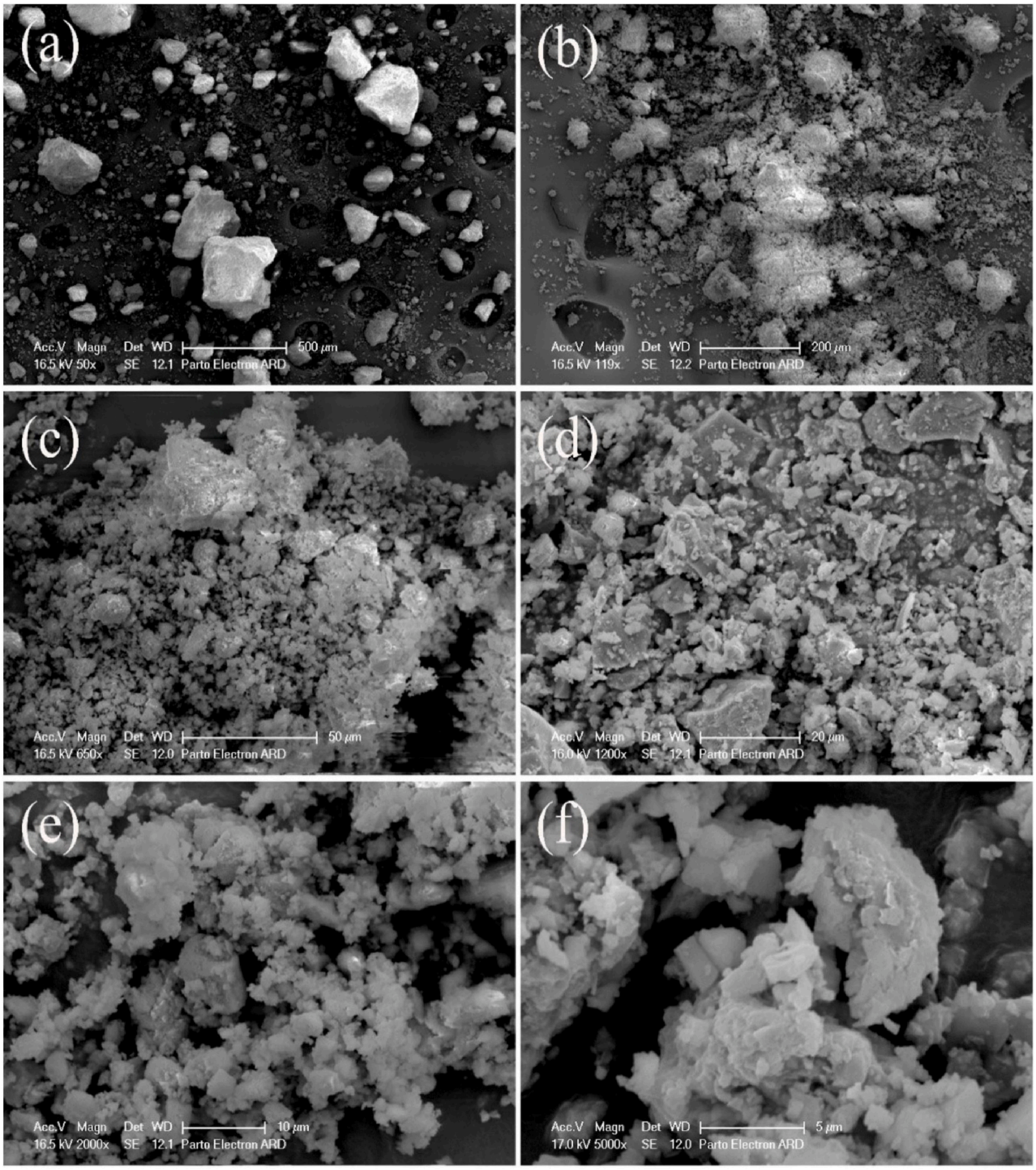

Fig. 3. SEM morphology of slag particles with different magnifications in different scales of (a) 500 μm, (b) 200 μm, (c) 50 μm, (d) 20 μm, (e) 10 μm, and (f) 5 μm.

on the efficiency of roasting process. So, slag size between 175 and 200 μm is a suitable slag size for handling the roasting process. The smaller agglomeration and decreasing the surface for chemical reactions for slag size more than 200 mesh are two main factors that decrease the roasting efficiency.

3.2. Effect of the roasting temperature and sodium carbonate

The effect of Na_2CO_3 % on the extraction of V within the range of 0∼20 % and at 500–1300 °C is shown in Fig. 6 and Eq. (1). According to Fig. 6, the recovery % of V with 0 % of Na_2CO_3 is very low. As can be seen in Fig. 6, there is a rapid increasing for roasting rate at the beginning and becomes constant after 1200 °C. This is due to the generation of calcium pyro vanadate which has a less solubility than sodium vanadate. Moreover, another reason is the creation of sodium pyro vanadate.

$$2NaVO_3+Na_2CO_3 \rightarrow Na_4V_2O_7+CO_2 \tag{1}$$

Fig. 6, shows that the maximum recovery% for the extraction of V is 91 % at 1100 °C by using 15 wt % of Na_2CO_3. By increasing the

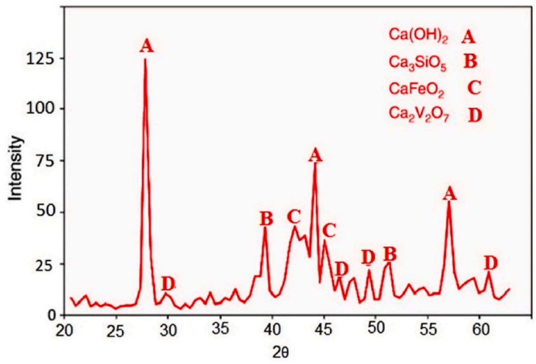

Fig. 4. XRD pattern of the slag sample.

roasting temperature more than 1100 °C, the recovery of V drops. Creation of insoluble glassy phases such as silicate compositions has an effective role on the V recovery [31]. Also, the roasting efficiency decreases by increasing the Na_2CO_3 Wt. % more than 15 %. So, after covering all slag particles by salt, the touch surfaces are between salt particles and it has not any effective influence on the roasting efficiency. So, using of 15 wt % of Na_2CO_3 at 1100 °C is the best ideal condition for the recovery of V during roasting process.

3.3. *Effect of roasting time*

Fig. 7 shows the effect of roasting time on the V recovery of steel slag at 1100 °C. Fig. 7 shows that high roasting time more than 50 min does not have any considerable effect on the recovery (%). Converting of calcium vanadate to sodium vanadate improves the recovery (%) during this 50 min. So, according to Fig. 7, the optimum condition for the roasting process is roasting with 15 wt % of sodium carbonate at 1100 °C for 50 min [31–34].

3.4. *Effect of the roasting atmosphere*

Fig. 8 shows the effect of controlled roasting atmosphere on its efficiency. Roasting parameters were a roasting time of 90 min at 900 °C, 15 wt % of Na_2CO_3 in mesh size of 175–200. The experiments were done in Argon, ambient atmosphere, moving ambient atmosphere and Oxygen. To this purpose, a circular furnace contains a controlled atmosphere has been used. The gas flow rate was 1 L/min and the composition of Argon gas was 99.9 Ar, 2 ppm (part per million) O_2 and 4 ppm of water. Fig. 8 shows that the roasting atmosphere has not a considerable effect on the V recovery during the roasting process. So, V with five electron capacities doesn't need to O_2 during the oxidation process. Usually, real oxidation condition in EAF is so severe that oxide compositions with high electron capacity should be presented in steel slags. Usually, it is reported that sodium carbonate stabilizes the higher electron capacity types of V element.

3.5. *Effect of cooling conditions*

Fig. 9 shows the effect of cooling condition on the roasting process. The roasting parameters were Na_2CO_3 15 wt %, slag mesh size 175–200 and roasting time of 90 min. As can be seen in Fig. 9, there is not any consideration change on the roasting efficiency by the cooling type. To handle the annealing process, slag particles have been annealed in furnace for 10 min at 800 °C. Decreasing in roasting efficiency during the rapid quenching in water is due to the creation of un-soluble glassy structure containing Na_2CO_3, sodium oxides, calcium and silicon phases. So during the rapid quenching, V is prisoned in glassy structure while during the slow cooling, crystalline phases are separated and V compositions remains near silicon structure.

4. Conclusion

The recovery of steel slag from EAF furnace at steel companies using alkaline roasting process have been studied. The following conclusions can be highlighted briefly.

- The composition of roasting process with 15 wt % of Na_2CO_3 for 60 min at 1100 °C is the optimum condition for roasting of steel slags.
- It is not necessary to use of oxidant materials when using of Na_2CO_3 as roasting agent due to the five electron capacity of V.
- At higher temperatures more than 1100 °C, the recovery (%) of V decreases due to the creation of glassy phases. These glassy phases are barriers against the formtion of chemical reactions.
- The best particle size for the recovery of V is 175–200 mesh size.

By using this method to recover V in the industry in future studies, it can help a lot in the treatment and prevention of cancer. The

Table 1
Chemical composition of the slag sample.

Compound(Oxides)	Fe_2O_3	CaO	SiO_2	MgO	Al_2O_3	TiO_2	V_2O_5	P_2O_5	Na_2O	MnO	SO_3	K_2O	MoO_3	Cl	CuO	SrO	ZrO_2	Y_2O_3	LOI.[a]	Total
Concentration (Wt.%)	35.48	28.81	18.90	7.78	4.26	1.36	1.31	0.518	0.480	0.374	0.140	0.125	0.058	0.034	0.034	0.021	0.019	0.009	–	**99.71**

[a] Loss on Ignition (1000 °C, 2 h).

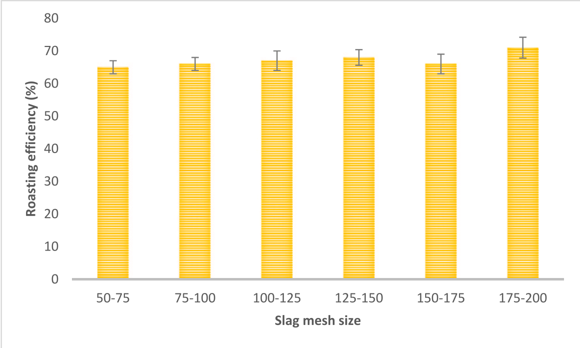

Fig. 5. Effect of slag mesh size on the roasting efficiency.

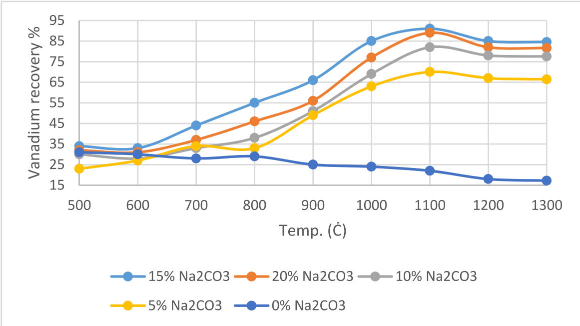

Fig. 6. Effect of roasting temperature and Na_2CO_3 Wt. % on the V recovery.

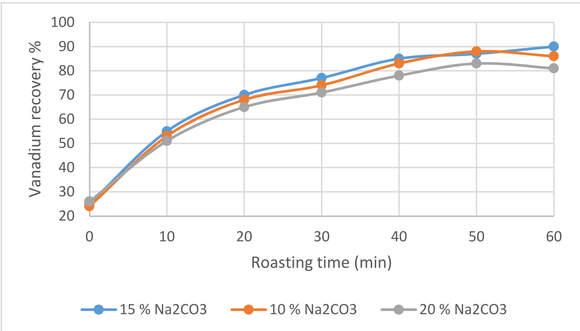

Fig. 7. Effect of sodium carbonate Wt. % and roasting time on the V recovery.

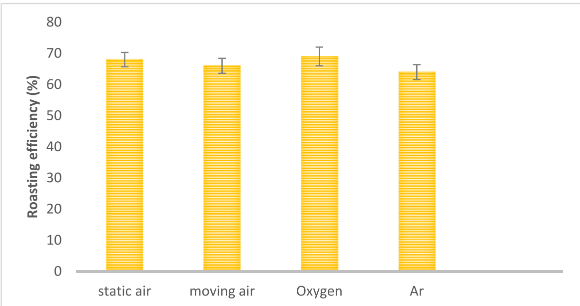

Fig. 8. Effect of roasting atmosphere on the roasting efficiency (%).

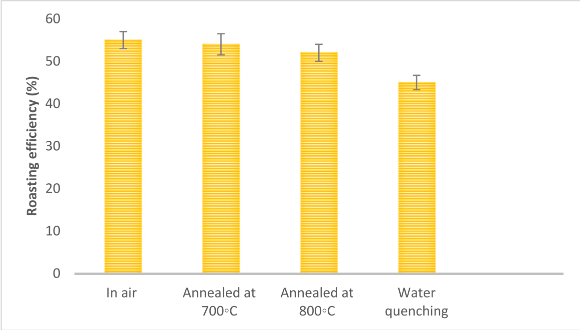

Fig. 9. Effect of cooling types on the roasting efficiency (%).

use of this anti-tumor agent can be very practical and the feasibility of comprehensive use of these particles will be investigated in the future.

CRediT authorship contribution statement

Mohammad Akbari: Writing – original draft, Data curation, Conceptualization. **Saeed Daneshmand:** Writing – original draft, Investigation, Formal analysis. **Mohammad Heydari Vini:** Resources, Methodology, Investigation. **Hamidreza Azimy:** Writing – review & editing, Visualization, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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