What are Green Flotation Reagents?

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Keywords: Green flotation reagents, sustainable raw materials, green production, biodegradability, low toxicity.

Abstract

In many published documents, researchers often call green reagents or eco-friendly materials, promising a more sustainable future in process beneficiation. However, no clear definition has been developed to categorize these additive chemicals for flotation operations worldwide. This study will focus on defining and classifying a green flotation reagent in depth, based on four main pillars: sustainable raw materials, green production, biodegradability, and low toxicity. The defined classification can be applied to the main key reagents, such as collectors, depressants, and frothers, and may support the comprehension of safety status or parameters that need improvement to achieve more sustainable operations from a chemical perspective. This investigation aims to provide a clear picture of the main reagent profiles used in flotation today and, therefore, establish the basis for developing new eco-friendly reagents.

1. Introduction

There is a growing demand for eco-friendly chemical reagents in minerals flotation, a widely applied concentration technique in mineral processing. Typically, traditional reagents, often derived from petroleum, may pose significant environmental and health risks due to their toxicity and persistence in ecosystems. Despite increasing interest in sustainable alternatives, there is no standardized definition or classification system for "green" flotation reagents. In this regard, a comprehensive definition and classification framework has been proposed in this work to evaluate and classify flotation reagents, based on four pillars: 1) safer chemical profiles; 2) biodegradability; 3) biobased raw materials; 4) green production processes. These pillars are weighted and integrated into a scoring system to assess the sustainability of collectors, depressants, and frothers, which represent the most important organic reagent categories in a flotation process.

Flotation is a water-intensive process, consuming 3 to 7 tons of water per ton of processed ore (Li et al., 2019). In countries such as Brazil, the US, and Australia, mining operations account for 1-2% of freshwater usage (Rao & Finch, 1989). Reusing or recirculating process water not only lowers the amount of freshwater required, as well as costs and environmental risks, but also reduces reagent consumption by up to 50% (Le et al., 2020). One of the challenges in flotation is related to the nature of the reagents applied, which can be toxic and non-biodegradable, leading to cumulative pollution. Some common flotation reagents include xanthates, that decompose into carbon disulfide (CS_2), a health hazard with aquatic toxicity; amines, surfactants that may be harmful to marine life; the depressant sodium cyanide, which is highly toxic and poses severe risks to humans and ecosystems; and also MIBC is moderately toxic to aquatic organisms (Wills & Finch, 2016) (Dong & Xu, 2011)(Rao, 2004) (ThermoScientific, 2022). These reagents may persist in the environment, bioaccumulate, and degrade water quality, encouraging the need for safer alternatives. Aside from the technical challenges, the geopolitical situation, including energy crises and conflicts that affect petroleum supply, further emphasizes the need for sustainable alternatives (Nabera et al., 2023) (BBC News - Hoskins, 2025).

Over the past decade, research on green flotation reagents has surged. Early studies focused on natural plant-based materials (mostly depressants) and biosurfactants (Banat et al., 2000). By the 2020s, research expanded to include biodegradable polymers and biobased collectors. This trend aligns with stricter regulations and industry efforts to reduce the environmental footprint of mining. Despite this progress, many studies lack rigorous classification and rely only on assumptions about biodegradability and renewability. Few incorporate ecotoxicological testing or life cycle assessments (LCA).

2. Green Flotation Reagents Definition Based on Green Chemistry

Anastas & Warner (1998) suggested the green chemistry can be defined according to 12 principles (P) summarized as follows: (P1) prevention of waste; (P2) atom economy; (P3) wherever practicable, design less hazardous chemical synthesis; (P4) design of safer chemicals; (P5) avoidance or application of safer solvents and auxiliaries; (P6) energy efficiency (ambient temperature and pressure, whenever possible; (P7) use of renewable feedstocks, whenever practicable; (P8) reducing derivatives; (P9) catalysis; (P10) biodegradation of products; (P11) safer analytical chemistry; (P12) accident prevention (Anastas & Warner, 1998) (Castiello et al., 2023). Based on Anastas & Warner's 12 principles of green chemistry, this article distills four core concepts applied to the mineral processing industry for green flotation reagents: safer chemicals (P4); biodegradability (P10); biobased raw materials (P7); and green production (P1-P3, P5-P6, P8-P9, P11-P12).

2.1. Safer Chemicals: Physical and Toxicological Hazards

Safety is the most important pillar of any organization; it is immediate and non-negotiable. A reagent must be non-toxic and pose minimal physical hazards. Key considerations include: 1) physical hazards, such as flammability and corrosiveness; and 2) human toxicity, acute toxicity measured via LD_{50} (oral/dermal) and LC_{50} (inhalation). The UN GHS system categorizes chemicals from Category 1 (most toxic) to Category 5 (least toxic). Chronic toxicity includes long-term effects like liver damage or carcinogenicity; 3) environmental toxicity, which is usually assessed via aquatic toxicity LC_{50} values for fish, crustaceans, and algae (United Nations, 2019). In line with this concept, it is well understood that biodegradability reduces bioaccumulation and long-term harm.

2.2. Biodegradability Concepts and Testing

Biodegradability is the action of microorganisms decomposing a material into CO_2 and water (ASTM, 2011) (Niemi et al., 1987). Readily biodegradable substances break down within 28 days under OECD test conditions. Inherent biodegradability tests are less stringent but more accurately simulate natural environments. Although microorganisms may adapt to degrade various substrates, including branched surfactants, chemicals structurally similar to natural biomolecules (proteins, oils, carbohydrates) are more likely to biodegrade (Farias et al., 2021) (Bragin et al., 2020). In flotation plants, biodegradability is crucial for water recirculation and effluent treatment. Poorly degradable reagents can reduce water quality and may also impact flotation efficiency, depending on the compound structure formed (Falconi et al., 2023). Biodegradability is also related to the safe discharge of effluent into the environment, thereby avoiding the application of advanced oxidative processes, such as Fenton and ozonation, which facilitates effluent treatment from both environmental and economic perspectives (Kumari & Kumar, 2023).

2.3. Biobased Raw Materials or Renewable Feedstocks

Biobased reagents are derived from biomass, including primary products (crops, such as maize, soy, and sunflower (e.g., for the production of starch and fatty acids)); primary residues: agricultural waste (e.g., straw, treetops); secondary residues: processing by-products (e.g., lignin); and tertiary residues: post-consumer waste (e.g., used frying oil) (Stralen et al., 2016). Examples include: starch (primary product), used as a depressant for hematite and kaolinite; lignosulfonates (as secondary residue): derived from lignin, used to depress pyrite; and fatty acids (from primary product or tertiary residue): applied in oxide and phosphate flotation (Hrůzová et al., 2020) (El-bahi et al., 2024). Biobased reagents are often biodegradable and renewable, but not always less toxic. Their performance can rival that of synthetic reagents, although variability and stability remain concerns.

2.4. Green Production – Sustainable Manufacturing

Green production emphasizes (P1) waste prevention, (P2) atom economy, (P3) avoid the use of hazardous reagents; (P5) use of safe solvents, (P6) energy efficiency, (P8) avoidance of derivatization, (P9) the use of catalysts, (P11) real-time monitoring linked to safer analytical chemistry, and (P12) accident prevention (Anastas & Warner, 1998). Examples of green solvents include isoamyl acetate and ethyl isovalerate from fusel oil (Bandres et al., 2011). Reactions under mild conditions (0–70°C) are preferred (McElroy et al., 2015). Catalysts can reduce energy needs and improve selectivity (Ahluwalia, 2013). Production processes must minimize the use of hazardous reagents and volatile substances (Ahluwalia, 2013). Collaboration between chemists and toxicologists is key to designing benign compounds.

3. Classification Framework for Green Reagents

This work introduces a scoring system based on the four pillars, represented by Tables 1 and 2. The levels of classification can be represented from 1 (the product fails to meet the minimum required sustainability parameters) to 7 (product made from biobased materials, produced via a green process, is non-toxic, and readily biodegradable. Ideal for the circular economy and minimal environmental impact). In Table 3, some of the main commercial reagents were analyzed. This evaluation was performed using safety data sheets from different compounds, the patents related to their production and differentconducted using safety data sheets from various compounds, patents related to their production, and academic articles. This means that the score here represented is for specific ways of molecules and production. Once this is changed or improved, the score should probably also vary, upgrading the total score of the material.

Table 1 – Criteria and weights.

Criteria	Weight (%)
Safer chemicals	
Human (H)	0/15
Environment (E)	0/15
Physical Hazards (PH)	0/10
Biodegradability	
No (N) – Partial (P) - Dangerous (D) / Yes	0/25
Biobased raw materials	
0%	0
≤ 25%	5
>25% ≤50%	10
>50% ≤75%	15
>75 ≤100%	20
Green process	
0-3 criteria	0
4-6 criteria	10
7-9 criteria	15

Table 2 – Classification of the reagents based on the weights of the main pillars

Level	Classification	Description	Colour Representation
1	Not Green	Points: 0-29%.	
2	Very low green	Points: 30-49%.	
3	Low green	Points: 50-59%.	
4	Moderately green	Points: 60-69%.	
5	Green	Points: 70-79%.	
6	Very green	Points: 80-89%.	
7	Fully green	Points: 90-100%.	

Table 3 – Analysis of some of the main reagents applied in flotation

Reagent	Function	Mineral	Biobased (%)	Green production (Y/N)	Safer chemical (Y/N)			Biodegradability (Y/P/D/N)	Classification	References
					H	E	PH			
Maize (corn) starch	Depressant	Hematite, kaolinite	100	Y (9-9 principles)	Y	Y	Y	Y	100	(Himashree et al., 2022)(EMBRAPA, 2025) (Rashwan et al., 2024)
CMC	Depressant	Carbonates, talc	65-90	N (4-9 principles)	Y	Y	Y	Y	90-95	(Arinaitwe & Pawlik, 2014)(Tasaso, 2015) (Churam et al., 2024)
Lignosulfonate	Depressant	Carbonates (i.e., calcite), quartz, sulfides (i.e., pyrite)	100	N (6-9 principles)	Y	Y	Y	Y	95	(Aro & Fatehi, 2017)(Karagoz et al., 2024)
Sodium silicate	Depressant	Silicates	0	N (5-9 principles)	Y	Y	Y	N	50	(Deabriges, 1980) (Carolina, 2025)
Sodium cyanide	Depressant	Gold, iron, and sulphides (pyrite, pyrrhotite, sphalerite, among others)	0	N (6-9 principles)	N	N	N	D	10	(Sigma-Aldrich, 1907) (Rogers et al., 1989)
TOFA	Collector	Apatite, calcite, and dolomite	100	Y (7-9 principles)	Y	Y	Y	Y	100	(Aro & Fatehi, 2017) (Kraton, 2023)
NPEO	Collector	Apatite	0	N (5-9 principles)	N	N	N	P	10	(United States Environmental Protection Agency, 2005) (McDaniel & Reese, 2009)
Isotridecanol ethoxylate	Collector	Apatite	0	N (5-9 principles)	Y	N	N	Y	50	
Isononylether-propylamine	Collector	Quartz and other silicates	0	N (4-9 principles)	Y	N	N	Y	50	(Koseoglu et al., 2021) (Fukushima et al., 2003)(Peres et al., 2000)
Sodium ethylxanthate	Collector	Copper, lead, nickel, zinc, gold ores.	28-32	N (4-9 principles)	N	N	N	D	20	(Keller, 1925) (Milosavljević et al., 2020)(Sigma-Aldrich, 2024b)
Sodium diisobutyldithiophosphate NaDIBDTP	Collector	Copper, molybdenum, zinc, and lead ores.	0	N (5-9 principles)	Y	Y	N	N	40	(Magalhães Baltar, 2021)(Gaspari, 1978)(ThermoFischer Scientific, 2024)(Sigma-Aldrich, 2024a)
MIBC	Frother	Sulfides and oxides	0	N (6-9 principles)	Y	Y	N	Y	65	(ThermoScientific, 2022) (ECHA, 2023)(Guinot, 1930)
Pine oil	Frother	Sulfides and oxides	100	N (6-9 principles)	N	N	N	Y	55	(Wills & Finch, 2016) (Sigma-Aldrich, 2025)(Spectrum, 2023)(ECHA, 2025)(Vallinayagam et al., 2014)

4. From Microcosm to Macrocosm: The Path

As shown in Table 3, some reagents are already being intensively applied in flotation; however, there is still a long way to go to improve the sustainability profile of these reagents. Chemicals with different sustainability profiles are already coexisting in the flotation environment, both in formulation (microcosm) and in various countries around the world (macrocosm). Each compound must be studied carefully and in detail to eliminate unnecessary hazards. It is possible to understand that changes will be implemented step by step, while keeping or improving reagent performance. As developing countries often lack regulatory frameworks, they can, for now, rely on standards set by countries that already have a strong regulatory system. Replacing hazardous reagents, such as sodium cyanide and xanthates, is more urgent. Alternatives such as isotridecanol ethoxylate offer better profiles but still rely on petroleum. Biosurfactants and biotechnological products hold promise but may compete with human applications.

5. Conclusion

A definition for a green reagent for flotation was established, with the goal of enhancing the understanding of the chemicals currently used for flotation. The four main pillars for the definition of green reagents were established: safer chemicals, biodegradability, sustainable raw materials, and green production. A classification framework was proposed as a means to establish the sustainability profile of reagents applied to flotation and those to be developed, aiming to enhance the sustainability profile of the process. This framework enables consistent evaluation and comparison. The gradual substitution of hazardous reagents is feasible and necessary for a long-term perspective. Furthermore, collaboration between the chemical and mining industries is crucial for driving sustainable innovation. This framework supports the selection and development of next-generation flotation reagents, aligning with environmental and safety goals, and paving the way for greener mineral processing.

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