Review Paper

Sulfur, an essential mineral in the agroecological management of agricultural systems

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Abstract

Objective: To evaluate the importance of sulfur as an essential mineral in the agroecological management of agricultural systems.

Materials and Methods: To develop this research, more than 80 scientific publications dealing with sulfur and sulfocalcic broth in agricultural systems were consulted. The fundamental role of these elements in the soil, their use by plants for pest prevention, as well as their effect on mites and ticks hosted by animals, and their value in ruminant nutrition were documented. Papers were also studied that address in the current context, the effects of climate change, the condition of the soil as the basis of all systems and the importance of agroecological management in agriculture and animal husbandry.

Results: Sulfur can be used in a variety of ways, as a soil pH reducer, fertilizer, pesticide and medicine for plants and animals. Its use in the manufacture of sulfuric acid and in ruminant nutrition is also contemplated. In addition, when combined with calcium as a sulfocalcic broth, sulfur is effective as an insecticide, fungicide, and medicine against mites and ticks. Its use is also necessary because 33 % of the soils in Cuba show a state of degradation ranging from moderate to high. This is due to various factors such as erosion, salinization, compaction, acidification and chemical contamination, which also causes the loss of biodiversity.

Conclusions: The use of sulfur or sulfocalcic broth is essential in agroecological soil management, due to the high percentage of areas with diverse affectations, to which its multiple applications in plants and animals are added. In Cuba, the use of this substance is a challenge due to the available quantities and the small doses that are used. However, their application facilitates the production of healthy and abundant food at low cost, without causing damage to the environment, and contributes significantly to human welfare.

Keywords: fertilizers, pest control, animal nutrition

Introduction

Sulfur, an essential natural element, is found in volcanic deposits, thermal waters and underground deposits. It appears combined with numerous minerals, such as pyrite and galena, and in the form of sulfates such as gypsum (Ramírez-Ortega and San-José-Arango, 2006). In Cuba, there are quarries with pyrite and flower of sulfur, derived from oil extraction.

Sulfur is a vital component of every living cell and forms part of several amino acids, such as cystine. Without it, plants cannot perform their basic functions. It is a macromineral and is classified as a secondary mineral, due to the amounts needed by plants and animals, but it is essential for the proteins required by plants, as part of their structure and of some hormones and oils (Quispe-Cusi *et al*., 2016). It is present in other sulfur biomolecules, such as biotin, taurine, coenzyme A, fibrinogen, heparin, thiamine and glutathione, so it has a very important role in cartilage integrity (Cardoso, 2021).

Sulfocalcic broth is one of the alternative products that can be produced from lime and flower of sulfur. It can become a potential environmental contaminant generated in the oil drilling, extraction and processing industry. The use of sulfocalcic broth in a strategy that includes agricultural crop management technologies, animal health practices and reduction of environmental contamination would make it possible to reduce agricultural pests, guarantee adequate yields and animal welfare, substitute imports and achieve higher quality and quantity of food production without affecting the ecosystem.

This mineral product was first recorded in the 19th century (Restrepo-Rivera, 2007a) and is widely used in Latin America by agricultural producers

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as fungicide-acaricide, permissible for use in organic agriculture, made from sulfur and lime slurry (Kondo, 2022). It is also used as fertilizer and pH stabilizer in acid soils. Its importance lies on the number of uses and the low doses used, making it non-toxic.

For countries that have sulfur available, its use is an opportunity at a time when fertilizer prices have tripled. The collapse of the three main sources of income of the countries of the South (food and vegetable products, hydrocarbons and various raw materials) led to a decline in the growth of their economies, due to the COVID-19 pandemic and the effects of the climate crisis caused by global warming (Ramonet, 2020).

The application of the results of science and the development of technological innovation processes in agriculture, focused on caring for the environment and the health of the ecosystem, as well as the application of circular economy, should have a direct impact on increasing agricultural productivity through the implementation of sustainable agri-food systems, with safe and healthy diets, higher water efficiency, soil conservation and regeneration and reduced greenhouse gas emissions, with a focus on equity for small farmers, native peoples and rural youth and women (Benítez-Fernández *et al.* , 2021).

Based on the above-explained facts, a literature review was carried out on the use of sulfur as an essential mineral in the agroecological management of agricultural systems, with emphasis on mineral-natural products, and its effect as fertilizer, pesticide and drug in plants and animals, respectively. The objective of the work was to evaluate the importance of sulfur as an essential mineral in the agroecological management of agricultural systems.

Materials and Methods

In order to carry out this research, more than 80 scientific publications dealing with sulfur and sulfocalcic broth in agricultural systems were consulted. The importance of this element and its derivatives for the soil was examined; in addition to its use in the prevention and treatment against pests that affect plants. Its effect on mites and ticks hosted by animals and its value in ruminant nutrition were also documented. In addition, papers addressing the effects of climate change in the current context, the condition of the soil as the basis of all systems and the importance of agroecological management in agriculture and animal husbandry were reviewed.

Results and Discussion

Importance of sulfur in agricultural systems

Sulfur is a mineral that, when heated, reacts with most elements except noble gases. It can be used in a variety of functions and in a variety of ways. It serves as a reducer of soil pH, it also influences electrical conductivity and micronutrients (Fe, Mn and Cu) which are increased by the application of elemental sulfur (Ondarse-Alvarez, 2022). Other functions of sulfur, referred to by Rodríguez-Acosta *et al.* (2006) are the following:

- It forms bisulfide (S-S) bonds between polypeptide chains by binding sulfhydryl (SH-) groups.
- It forms covalent bonds between different chains or within the same polypeptide chain, thus increasing the stability of their structures.
- Promotes nodulation of legumes.
- It participates in oxidation-reduction reactions, being a component of ferrodoxins, among other compounds, which helps the development of enzymes and vitamins.
- Contributes to seed production.
- It is necessary in the formation of chlorophyll, although it is not a constituent of this compound.
- It is responsible for the characteristic odor present in garlic (*Allium sativum* L.), mustard [*Brassica juncea* (L.) Czern] and onion (*Allium cepa* L.).
- When added to cassava, it reacts by eliminating the action of hydrocyanic acid.
- It forms part of the hormones hemoglobin and insulin.

A report by FAO and GTIS (2016) states that 33 % of the earth's soils are moderately to highly degraded due to erosion, salinization, compaction, acidification, chemical contamination and loss of biodiversity, which threatens food security and increases global poverty rates. However, it is known that the soil resource is responsible for maintaining 95 % of food production, hosts more than a quarter of the planet's biodiversity, is an important source of pharmaceuticals and plays a key role in the carbon cycle (UNCA, 2015), in addition to being the base of the pyramid on which the entire cultural development of society is based (Burbano-Orjuela, 2016).

In Cuba, according to data from the Ministry of Agriculture (MINAGRI), only 28 % of soils are located in categories I and II, according to their productivity; 71 % are affected by erosion (43 % from strong to moderate), 70 % have low organic matter content, 15 % have salinity and more than 2 million hectares have acidity (Fernández-Salinas, 2021).

This threatens the country's food security and sovereignty and has implied the development of environmental policies, supported by international projects funded by the United Nations Environment Program (UNEP), aimed directly at improving soil use.

In 2021, MINAGRI approved the policy for conservation, soil improvement, sustainable soil management and fertilizer use (Consejo de Ministros, 2021). This policy has a decree-law, a decree and four ministerial resolutions, aimed at favoring sustainable agro-productive systems and improving state control for the protection, conservation, improvement, rehabilitation and management of soil, as well as for the use of fertilizers.

There are different alternatives for the improvement of soil functions for agriculture, such as the application of organic and organic-mineral fertilizers, compost, intercropping of leguminous plants and green manures, among others, as well as the use of different inoculants in the areas of seed production and forage, with excellent results.

The best agricultural system that will be able to face future challenges is the one based on agroecological principles that exhibit high levels of diversity and resilience, while offering reasonable yields and ecosystem services, with healthy food, contributing not only to feeding but also to human well-being and health.

Paniagua-Vargas and Garcia-Oliva (2022) in a review paper on sulfur mineralization and immobilization in soil concluded that these processes are microbiologically controlled, and that they occur simultaneously. Their dynamics largely determine the nature of sulfur compounds and their bioavailability to plants and other organisms.

The strategies for sulfur mineralization are diverse and respond to the need for sulfur energy: biological or biochemical mineralization. Both processes depend on the genetic heritage of the soil microbial community (SMC), because if the genes encoding specific enzymes are not present, sulfur mineralization and immobilization will not take place. Understanding how the processes of sulfur dynamics are carried out in the soil will allow making better decisions about its fertilization and conservation, provided that edaphic microorganisms are considered to be the ones that sustain its dynamics.

Agricultural crop production systems, in general, are affected by erosion, nutrient imbalance, loss of biodiversity due to overexploitation, poor agriculture-animal husbandry integration and acidification, among other aspects.

According to Pezo (2019), factors that are related to bioprotection and climate conditions should also be considered. In low-latitude countries with seasonal droughts, crop productivity will be reduced due to the displacement of populations of pollinator species and biological pest and disease controllers.

In addition, growth, flowering and fruit ripening are accelerated by high temperatures, resulting in higher evapotranspiration and increase in the probability of water deficit in crops, together with the growth of populations and the length of the seasons, not to mention the development of pests and the increased incidence of diseases and their spread to new areas. The rational use of water and energy is also an imperative for food production (Montoriol-Garriga, 2022).

Regarding animal husbandry systems, overgrazing deserves special mention. It occurs in systems that are poorly managed by man, where pastures do not recover from frequent defoliation, due to the lack of plots or quarters that allow adequate rotation and the necessary rest. In addition, in these systems, nutrient extractions from the soil are not replaced with fertilizer, which causes the disappearance of established cultivated species and soil compaction. These conditions accelerate erosion by reducing soil mesofauna and macrofauna and affect the biodiversity of the agroecosystem and, therefore, its physical and chemical characteristics.

In this degradation process, pastures lose their support capacity, production per animal is reduced and, consequently, the animal productivity potential of the system decreases. In addition, there is an ecological impact, as the capacity to capture and accumulate carbon is reduced and the emission of CH_4 per kilogram of animal product increases (Pezo, 2019).

Most of the time, animal stocking rate is blamed for overgrazing. However, there are two factors that have the greatest impact on pastureland deterioration: not having enough pastures and not maintaining the balance between plant nutrient extraction and plant nutrient demand. Not managing with the necessary rest after the animals leave the pasture does not allow the recovery and growth of the established species. Likewise, not restoring the nutrients extracted by the species in each rotation causes physiological deterioration and the disappearance of the species, as well as compaction and the disappearance of the soil fauna.

Agroecology plays a crucial role in defining the future of food systems. As Holt-Giménez and Altieri (2013) point out, the building of strategic alliances by agroecologists in the struggle for food sovereignty could strengthen a movement capable of generating considerable political will to transform food systems. The promotion of smallholder farmers, elimination of hunger, restoration of agrobiodiversity and resilience of the planet's agroecosystem would be better served in such a scenario.

Diversified agroecosystems, which integrate agriculture and animal husbandry, use agroecological management based on the conversion of conventional systems to systems that are resilient to climate changes, with the use of biofertilizers, organic-mineral fertilizers, bioproducts and food produced in the farms (Vázquez-Moreno, 2020). There are also mineral resources that, used sustainably, can become new agroecological alternatives to replace imported inputs, including sulfur and lime, with innumerable benefits for the soil and for the management of pests in crops (García-Sánchez *et al.,* 2022) and mites in animals (Wright, 2012).

Effect of sulfur on agricultural crops

Sulfur deficiencies can be corrected with the use of fertilizers containing this element or with direct applications of a sulfur compound. The choice between one or the other method will generally depend on economic factors, but direct applications in doses of 10 to 50 kg/ha are preferable.

In agriculture, sulfur is used in different forms: in powder form and with calcium-based compounds, mainly to treat crop diseases (Restrepo-García and Soto-Giraldo, 2017). Despite not being soluble in water, it can be prepared in the form of excellent emulsions that make its use in sprays viable.

Integrated application technologies of this mineral with bioproducts have had favorable effects on pest reduction and crop yields. Morales-Soto *et al*. (2019) when evaluating the effectiveness of the fungi *Lecanicillium lecanii* (Zimm) Zare & Gams, *Trichoderma harzianum* Rifai and *Metarhizium anisopliae* (Metsch) Sorokin, at a dose of 1 012 conidia/ha and, sulfur, at a dose of 3 kg/ha, applied with a weekly frequency on the leaf area of common bean (*Phaseolus vulgaris* L.), variety CC-25-9N, registered a substantial reduction in the populations of insects thrips (*Thrips palmi* Karny), leafhopper (*Empoasca kraemeri* Ross & Moore) and whitefly (*Bemisia tabaci* Gennadius); although the greatest effect was reported on *Metarhizium* and *Lecanicillium*. The applications with the fungi and sulfur also had a positive effect on crop yield and its components.

Sulfocalcic broth is, in a general sense, a preparation based on sulfur and quicklime, commonly used in organic agriculture for the control of fungal diseases. Although it is considered an inorganic insecticide, its use is allowed in organic agriculture because it has no negative effects on production and the environment. Different authors (Sierra *et al*., 2007; Restrepo-Rivera, 2007b; Kondo, 2022) propose formulations and manufacturing methods for the use of sulfocalcic broth, in which different proportions of sulfur, lime and water are used. However, integrated systems with ash, biochar, and minerals, among others, are reported, depending on the crop in question (Restrepo-Rivera, 2007a).

The use of sulfocalcic broth as a pesticide, fertilizer and drug (to treat diseases caused by ectoparasitic mites in animals) was first recorded in the 19th century (Restrepo-Rivera, 2007a) and then industrially in Spain, Brazil and China. In artisanal production, it is used in Mexico, Costa Rica, San Salvador, Honduras, Brazil, Colombia and other countries.

Its use has been documented in the world and the literature refers that it is produced at an industrial level, but it can also be elaborated in an artisanal way. There are manuals, booklets and illustrated leaflets that explain how to elaborate it with different doses and proposals for its use in small farms. There is also specialized literature on application rates, time of use and crops that are more sensitive to its use. Its use has been documented in fungal diseases of *A. cepa* L. (onion), *P. vulgaris* and *Persea americana* Mill (avocado), as well as in the treatment against thrips and mites in *A. cepa*, garlic, in *B. cockerelli* of *Solanum tuberosum* L. (potato), in CBB of *Coffea arabica* L. (coffee), among other ailments (Cabrera-Marulanda *et al*., 2018; Córdova-López, 2018; Gramaglia, 2019; Chamorro-Guerrero, 2023).

Certain cucurbit varieties, peach and apricot, between flowering and fruit set stages may show phytotoxic application problems. In these cases, a test at low doses is recommended. The possible effects reported are due to the presence of copper in sulfur and magnesium in lime. In addition, their effect on anthracnose is known.

According to reports by INTAGRI (2017), sulfocalcic broth is not toxic for mammals and for bee species its toxicity is low. In any case, if pollinators are used, a series of precautions must be maintained so as not to limit the performance of bumblebees. Although it is not usual, in some cases of very repeated applications of sulfur, the phytoseed populations can be unbalanced. It can be phytotoxic at temperatures above 28 °C, but if applied at low temperatures its action is not very effective.

It acts on microorganic agents that produce diseases in crops, including: *Sphaerotheca pannosa*, *Sphaerotheca fuliginea*, *Sphaerotheca humili*, *Sphaerotheca morsuvae*, *Microsphaera grossulariae*, *Microsphaera quercina*, *Microsphaera alphitoides*, Podosphaera *leucotricha*, *Podosphaera clandestina*, *Podosphaera tridactyla*, *Oidium mangiferae*, *Oidium caricae*, *Oidium heveae*, *Oidium tingitaninum*, *Erysiphe graminis*, *Erysiphe cruciferarum*, *Erysiphe betae* and *Erysiphe heraclei* (SADER, 2022).

In general, for the use of the broth on crops, it is recommended not to fumigate or apply it to bean, kidney bean, broad bean or other leguminous crops when they are in flower. It should not be applied to plants of the cucurbitaceous family (cucumber, watermelon, melon, pumpkin), since in most cases it burns them. It is also suggested to use it preventively (before fungal attack), every seven to ten days and to pack the product in dark (matte) jars.

From the point of view of human health, it is advisable that when handling or applying this product, adequate protective equipment (overalls, glasses, mask, cap, gloves and rubber boots) is used, to avoid contact with eyes and skin, and not to eat, drink or smoke while handling the product. After applying it, it is recommended to take a bath and put on clean clothes.

In Cuba, sulfur is an insecticide certified by CENATOX[1] (2006), in the Central Register of Pesticides of the Republic of Cuba. It is on the official list of pesticides authorized for use on different crops, imported from different countries.

When sulfocalcic broth with native microorganisms and bioproducts was applied to the *Phaseolus vulgaris* L. crop in areas of productive entities in Cuba, in 2020, yields were between 1,3 and 1,8 t/ha, results that exceeded the national historical average of 0,4-0,6 t/ha (Medina-Salas and Milera-Rodríguez, 2023).

According to the visual observations made during field monitoring, the presence of *Megalurothrips usitatus* (Bagnall), flower thrips of *P. vulgaris*, and of pathogens causing fungal diseases, mainly rust, was low and not very representative. In addition, the plants were vigorous and flowering was fairly uniform, which may have favored the yield obtained.

Medicinal effect of sulfur on domesticated animals

In animals, sulfur is found in a proportion of 0,25 % and is located in the protective tissues, such as skin, hair, horns, nails and wool. This mineral has a plastic function in the organism, as a component of the structures of the epidermis, in which sulfur amino acids are abundant (wool contains 4 % sulfur). It is an essential macroelement for the formation of amino acids such as cystine, cysteine, homocysteine, methionine, taurine, although some vitamins such as biotin, thiamine, the hormone insulin and hemoglobin contain sulfur. In a general sense, the minimum sulfur requirements for cattle are between 0,1 and 0,3 %, on a dry basis. The maximum tolerance level is 0,4 % of the total diet.

Sulfur is also a mineral of high importance in the digestive physiology and nutrition of ruminant animals. It is known that the rumen is a complex ecosystem, where the consumed nutrients are digested through a fermentation process carried out by rumen microorganisms (bacteria, protozoa and fungi), producing low molecular weight fatty acids and microbial proteins, which are used by the animal.

These microorganisms need mineral substrates, such as sulfur, which promote their growth and ruminal development. Its absorption by ruminants is mainly in the form of sulfate or as sulfide ion. These compounds can be used more efficiently by rumen microorganisms than elemental sulfur for the formation of microbial biomass.

When there is sulfur deficiency, and the proportion between nitrogen and sulfur is not adequate, this has an impact on microbial synthesis and fiber degradation in the rumen, which leads to a decrease in dry matter intake and affects the growth rate of animals, milk production and

[1]Cuban National Toxicology Center

other products, such as wool (Cardoso, 2021). Its prolonged deficiency, or its excess, can cause low yields, neurological alterations and even death.

In animal husbandry practice, elemental sulfur, in the form of flower of sulfur, is used in mixtures or mineralized salts, at a rate of 8,0 %, with a salt intake of approximately 100 g daily (Ávila-Ferrufino and Calderón-Jarquín, 2020), with beneficial effects in the elimination of ticks, without affecting animal production. Moreno-Castellón (2021) demonstrated the effectiveness of sulfur at 8 % in dairy concentrate feed on tick repellency (96 %), without affecting milk production and with economic results superior to those obtained with the use of traditional repellents.

Paternina-Durango *et al*. (2015) obtained repellency levels higher than 90 %, when they used this mineral product in doses of 8-10 % in mineralized salts. It has also been used as a tonic, a practice that was carried out ancestrally by many cattle farmers in the eastern plains of Colombia, since in addition to the beneficial effect on tick control, the animals, show a lustrous and shiny coat due to its effect on the skin, which makes them improve their external appearance (Villar-Cleves, 2006).

Regarding its use against mites in animals, Antipa-Rivera *et al*. (2014) recommend farmers to have the option of sulfocalcic broth, at a rate of 20 % over volume of water, every 21 days, to break the tick cycle and obtain a better control of the parasite.

Cabrera-Chavarria and Téllez-Gamboa (2019) used sulfocalcic broth, combined with treatments of natural origin from plant extracts (*Azadirachta indica* A. Juss., *Gliricidia sepium* and *Eucalyptus* spp) in various proportions. The level of tick infestation decreased by more than 60 % after the application of all natural treatments, with effects similar to those of the commercial treatment (Asuntol 20 % SL).

In Cuba, sulfur obtained as a by-product of oil extraction is not used to its full potential in the chemical industry or in the production of fertilizers. This could become an opportunity if sulfocalcic broth were produced for agricultural systems.

Currently, in Matanzas province, the possible use of the flower of sulfur generated in the ENERGAS plant, in the Cárdenas municipality, is being evaluated for the elaboration of sulfocalcic broth and its application in agriculture and animal husbandry. Given its purity, of more than 99 %, and its availability, it constitutes an alternative for substituting imported inputs in agriculture.

Final considerations

The use of sulfur or sulfocalcic broth is essential, due to the high percentage of areas with soils affected in different ways, as well as for the multiple uses it has for its application in plants and animals.

In Cuba, the use of this substance is a challenge due to the available quantities and the small doses that are used. Nevertheless, their use facilitates the production of healthy and abundant food at a low cost, without causing environmental damage, in addition to contributing significantly to human welfare.

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Authors' contribution

- Milagros de la Caridad Milera-Rodríguez. Carried out the bibliographic review, as well as the paper writing and revision.
- Osmel Alonso-Amaro. Participated in writing and revising the paper.
- Jesús Iglesias-Gómez. Participated in revising the paper.
- Rafael Medina-Salas. Conducted the observation tests in productive areas.

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