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IMPACTS OF GLYPHOSATE (ROUNDUP®) ON THE ENVIRONMENT AND ON HUMAN HEALTH

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ABSTRACT

The use of agrochemical products for the control of pests has been widely extended on a global scale in commercial agriculture, despite its impacts on human health and on biodiversity. Glyphosate is the most commonly used herbicide, with adverse effects on human health and the environment that have led to controversy in the technical-scientific arena. The aim of this essay was to identify the main researches/studies related to the herbicide glyphosate and record its impact on the biota, the environment and public health. In order to do this, a bibliographic search was carried out, limited to scientific articles in Scopus between 1980 and May, 2022. The search criteria were: glyphosate, Roundup®, toxicity, environmental impact, human health, water pollution, underground and surface water and nonpoint sources. A total of 1607 articles was found, with an increase of 178 % in scientific production in the last 10 years. The countries with the highest number of publications related to the topic of glyphosate were developed nations with intensive agriculture. Mexico is in sixteenth place, with 29 (1.8 %) scientific articles for the period studied, out of which only 17 % are studies in bodies of water. Based on the literature consulted and the co-occurrence map, the elements that are related to the impact on the bodies of water by glyphosate are the type of agriculture, location of the fields, rainfalls and the characteristics of the catchment area.

Keywords: nonpoint source pollution, toxicity, agriculture, pesticides, agroecosystems.

INTRODUCTION

The use of pesticides in agriculture has increased considerably since the mid-20th century. An example of this are herbicides, which have become increasingly used in the last 20 years. This increase in the use of pesticides in agriculture, its effects on the environment and on human health were first pointed out by Rachel Carson in her book "Silent Spring". This motivated a change in paradigm, giving way to movements such as organic agriculture, the emergence of educational programs in environmental topics and a strong environmentalist trend globally. Despite this, in some countries there is a tendency to increase use and in others, to decrease it (Schreinemachers

and Tipraqsa, 2012). Countries such as Austria, Vietnam, France and Germany have established agroecological policies to reduce the dependence on the use of pesticides, environmental pollution and its effect on human health (Tataridas *et al*., 2022).

From the standpoint of conventional agriculture, plants known as weeds are considered undesirable since they compete for sun light and soil nutrients, which impacts crop yields (Page *et al*., 2012). Diverse control strategies have been used for their eradication, including the use of glyphosate. This is the most widely used control strategy in the world, and it is classified as a systemic, wide-spectrum and non-selective herbicide that goes back to the 1970s, patented by the company Monsanto under the brand name of Roundup® (Beckie *et al*., 2020).

The prohibition of glyphosate in the countries mentioned is due to its identified toxic effects on human health and on the biota, whether by direct or indirect contact. Glyphosate has been reported to be a potentially carcinogenic compound, as well as a trigger for severe damages on organisms and the environment (de Carvalho Marques *et al*., 2021). Other authors indicate that its use is close related with environmental pollution, the drastic reduction of bee populations (Ruíz-Toledo and Sánchez-Guillen, 2014), effects on the soil nutrient cycle, particularly carbon and phosphorous, and the pollution of bodies of water and the aquatic biota (van Bruggen *et al*., 2018). Therefore, the aim of this essay was to identify the main studies published related to the application of glyphosate and its impact on the biota, the environment and human health, under the hypothesis that the effect of Roundup® on the environment is still ambiguous and inconclusive.

Use in agriculture

Glyphosate is a wide-spectrum, non-selective, foliar-action, post-emergent and systemic herbicide, which became highly relevant after the introduction of transgenic crops. The massive and intensive use of glyphosate in agriculture worldwide is due largely to its availability and low cost in the agrochemicals market. According to Benbrook (2016), the use of glyphosate increased considerably on a global scale; only between 1993 and 2019 (26 years), the use of herbicides tripled, including the use of glyphosate (Figure 1).

The main use of glyphosate as a herbicide is eminently agricultural, to eliminate narrow and broad leaf and woody plant species, mainly in maize, bean, wheat, citrus, tomato, vines, cotton, soybean, sorghum, sugarcane and potato plantations in ornamental crops and in forest plantations (Hernández-Ríos *et al*., 2018). Transgenic crops have been reported to generate an increase in the use of glyphosate, including maize, cotton, soybean, potato and canola (Benbrook, 2016).

Glyphosate also has non-agricultural uses, to control weeds on the sides of roads, paths, gardens or vacant plots in urban areas, but also in lagoons and dams, to control aquatic weeds (Salazar-López and Aldana, 2011). In the herbicide market, glyphosate is the active ingredient in hundreds of products. According to COFEPRIS, some commercial names iclude Roundup, Faena, Novasato, Glyfos, Glissan, Gabycord,

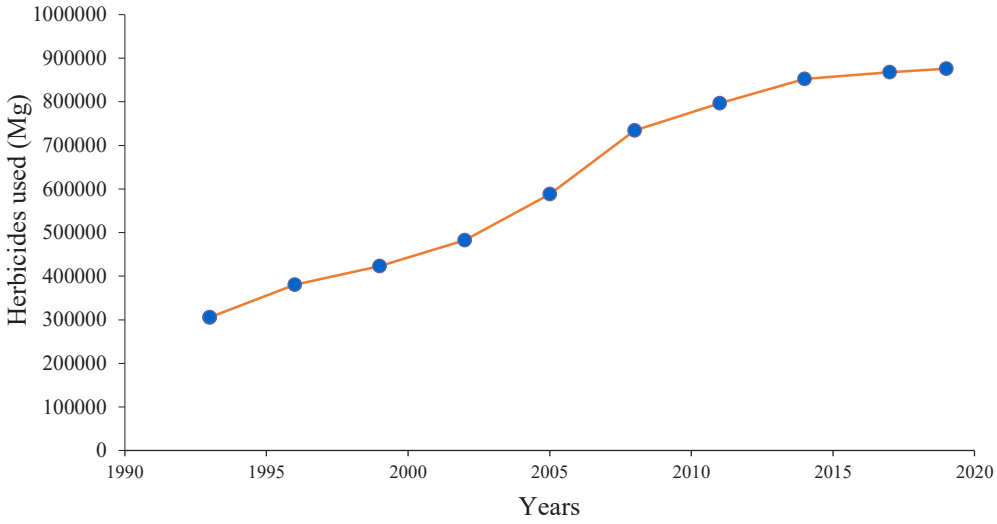

Figure 1. Herbicides used (Mg) in the 1990-2019 period in Canada and Latin America (FAO, 2022).

Lazer, Yierbasato, Sanfosato, Glyfan, Glifobest, Unifo-sato, Shadow, Suprim, Lafam, Takle, Arraza, Yerbimat, Mamba, Sankill, Aquamaster, Ramrod, Velfosato, Eurosato, Durango and Cacique 480.

Impact on the quality of water

Water is a crucial resource to guarantee food security through agriculture (González-Villarreal and Arriaga-Medina, 2020). However, bodies of water worldwide currently display high levels of pollution and eutrophication due to the use of inputs in agriculture, including fertilizers and pesticides (FAO, 2018). Maintaining water quality is vital in environmental terms and for human health on the planet, particularly in times where water tends to be a scarce and highly polluted resource.

There is evidence that indicates that glyphosate is one of the main pollutants of surface and underground water. Its presence in high concentrations in bodies of water is related to intensive and extensive agriculture, in which the use of glyphosate is frequent (Mas *et al.*, 2020). Salazar-López *et al.* (2016) point out that the main way of access to bodies of water is through nonpoint sources, that is, through runoffs of agricultural fields. Zirena-Vilca *et al.* (2018) indicated that the particles of glyphosate and its metabolite, amniomethylphosphonic acid (AMPA) may remain in water in its particulate phase or dissolve completely. It is important to point out that many bodies of water are used for the public supply of water, and even when they are treated, not all residues are identified and eliminated.

Impact on the biota

Glyphosate affects every terrestrial or aquatic organism that comes into indirect contact with it. It has been reported to affect the microbial community in the soils, which could alter biogeochemical cycles (Mohamed *et al*., 2021) and the growth and reproduction of earthworms, jeopardizing the nutrient and soil cycles. In fish, amphibians and reptiles, adverse effects have been documented, including endocrine disorders, hepatotoxicity, genotoxicity, neurotoxicity, cardiotoxicity, morphological alterations, alterations in embryonic development and mortality (Nunes Rezende *et al*., 2021). In the case of bees, the use of glyphosate is related to the reduction of their population (Ruíz-Toledo and Sánchez-Guillen, 2014), which jeopardizes the agricultural production of crops that require pollination.

Impact on human health

The absorption of glyphosate in humans may be due to direct or indirect contact, whether through the skin, because of its continuous use with no protection during its handling, and indirectly via ingestion of glyphosate or contaminated products. In 2015, the International Agency for Research on Cancer (IARC, 2015), an agency that is part of the World Health Organization (WHO), declared glyphosate as a probably carcinogenic compound, a controversy that is still being analyzed. There are studies that indicate the presence of glyphosate residues, along with its main degradation metabolite, aminomethylphosphonic acid (AMPA), found in foods. Although it is not a bio-accumulative compound, it is a threat to public health if its concentrations exceed the maximum permissible limits established by the *Codex Alimentarius*.

There is a wide range of human disorders and diseases related to the formulations of glyphosate-based herbicides. Some researchers include the following in the main anomalies found: metabolic alterations, damage to DNA, kidney damage, attention deficit disorder with hyperactivity (ADDH), Alzheimer, Parkinson, autism, leaky gut syndrome, non-Hodgkin lymphoma and anencephaly (Zhang *et al.,* 2019). In Mexico, Rendón-von Osten and Dzul-Caamal (2017) reported traces of glyphosate in the urine of agricultural workers and groundwater, as well as in samples of bottled water. In the year 2018, in the United States, a case was published in which an agricultural worker had developed terminal cancer (non-Hodgkin lymphoma) due to the frequent exposure to products such as Roundup® and Ranger Pro® (Hernández-Sierra *et al.,* 2021).

MATERIALS AND METHODS

A systematic search was performed for scientific references made in the last forty years in the Scopus data base. The search criteria were glyphosate, Roundup®, toxicity, environmental impact and human health. This search, limited to scientific articles, produced a total of 1607 references. With the help of Scopus, the bibliometric analysis was obtained, which gave the scientific production per year and the main countries with the highest number of articles published. Later, taking the most used keywords in

the titles and the abstracts of each scientific article as a unit of analysis, a co-occurrence map was created, using the program VOSviewer version 1.16.17. Within the network, the search keywords were located and their ego networks (all the connections that go in and out of these nodes) were visualized.

To obtain a visualization of the map, VOSviewer applies the association strength normalization technique, the visualization of similarities or VOS mapping and finally, the cluster technique. A cluster is a set of nodes, broadly related depending on the type of link analyzed; each node is assigned exactly to one cluster. Finally, a second specific search was carried out for articles related with the pollution of water with glyphosate. For this, the following terms were taken as search criteria: water pollution, underground and surface water nonpoint sources, glyphosate and Roundup®. This new search gave a total of 172 references and a co-occurrence map was created using the program VOSviewer version 1.16.17.

RESULTS AND DISCUSSION

Bibliometric analysis

The scientific production related with the impact of the use of glyphosate from 1980 to 2022 has a considerable increase starting in 2010, which is broadly related to the increase in the use of glyphosate-based herbicides in the last twenty years. In the last ten years, scientific production increased 178 % (Figure 2). In the first quarter of 2022 alone, fifty-six publications were found, which represent 26.4 % of the previous year. In 2015, the WHO declared glyphosate as a "likely level 2 carcinogenic compound (moderately dangerous)", which positioned it as a matter of world interest, giving way to studies related to this compound. Practically, in the last 20 years (2002–2022)

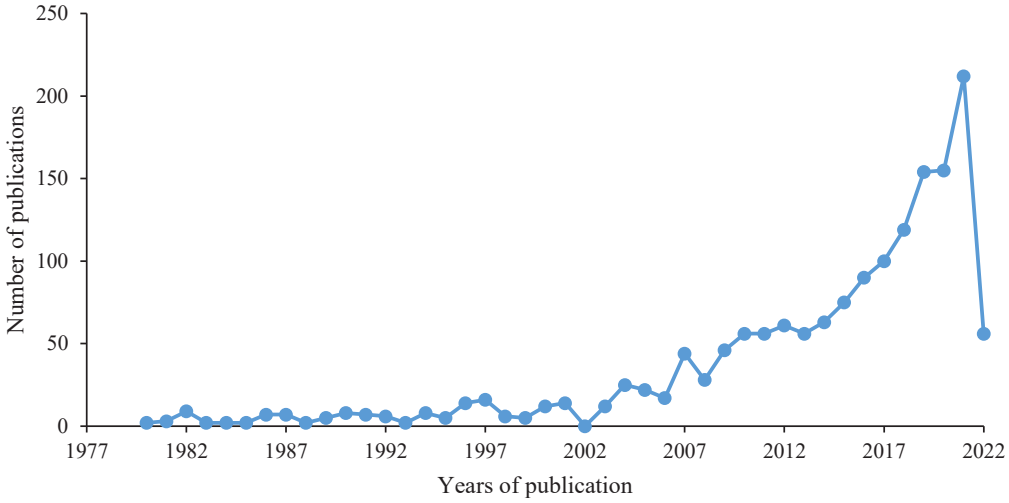

Figure 2. Scientific articles published worldwide related to the use and impact of glyphosate in the last forty years.

there has been an exponential growth ($y = 1E - 109e^{0.1267x}$) in publications related to glyphosate, reaching a total of 212 in 2021.

The countries with the most publications on the topic are the United States, followed by Brazil, China, Argentina, Italy, France, Canada, India, the United Kingdom and Germany, all of which have more than 50 publications. Mexico was sixteenth, with 29 (1.8 %) publications for the period under study (1980–2022), in which studies were found that study the presence of glyphosate and/or metabolites in humans, plants and animals (24 publications), and to a lesser extent, its presence in bodies of water (5 publications). This shows the few studies carried out on the topic in Mexico.

Keywords: impacts on human health

The network of co-occurrences of the keyword shows that the central and most mentioned word was "glyphosate", around which other recurrently mentioned terms link, and which take a central place in the network of keywords (Figure 3). The main related glyphosate toxicity results in the literature were genotoxicity, neurotoxicity, cytotoxicity and endocrine disruption.

Environmental impacts come mostly from the high use of glyphosate in agricultural fields and they relate to the pollution of soils, of surface and underground water, foods, as well as with alterations in the biota and in humans. There are reports of the presence of glyphosate in foods such as honey, fruit, cereals, dairy formulas, legumes and produce (Savini *et al*., 2019). This shows that glyphosate does not degrade

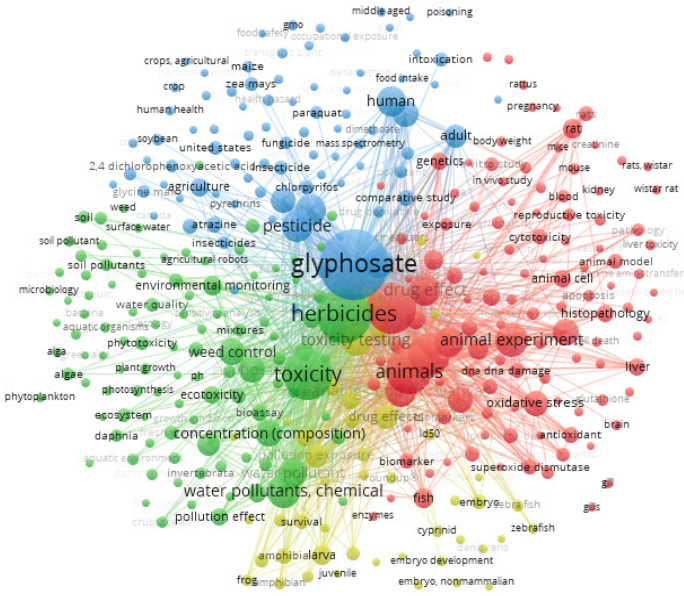

Figure 3. Network of co-occurrences of keywords related to the investigations of the impact of glyphosate worldwide.

completely and that part of this compound is transferred directly onto foods, onto terrestrial and aquatic organisms after its application, and onto humans, by direct and indirect contact. In recent years (2010–2022) it has become known that glyphosate causes alterations in the biota and in humans (Table 1). The pathologies presented could promote the development of cancer and other diseases.

Table 1. Impacts of glyphosate on the biota and in humans.

Organism	Effects	Reference
Nematodes and worms	Mortality in exposures of over 1.76 mg L^{-1}, changes in behavior, growth and reproduction.	Zaller *et al.,* 2021.
Crustaceans	Size reduction in its juvenile state, reduction in growth rate, damage to reproductive capacity and low survival rate.	Bordin *et al.,* 2022.
Microalgae, algae and seagrasses	Reduction in chlorophyll content, photosynthesis and respiration.	Kittle and McDermid, 2016.
Bees (*Apis mellifera*)	Reduction in cognitive ability and cell death in larvae.	Balbuena *et al.,* 2015.
Fish	Premature hatching, heart insufficiency, swim bladder failure, body malformation, behavior changes and oxidative stress.	Liu *et al.,* 2022.
Rats and hares	Morphological and functional changes in the intestine and in behavior.	del Castilo *et al.,* 2022.
Humans	Severe eye irritation, moderate skin irritation, genotoxicity, neurotoxicity, neurodegenerative diseases.	Tarboush *et al*., 2022.

Keywords: impacts on water

The network of co-occurrences of keywords that refer to the pollution of water with glyphosate show that the central and most frequently mentioned words were “glyphosate” and “pollution”, around which secondary terms can be observed, such as agriculture, drinkable water, surface and underground water, residues, ecotoxicology, animals, applications, soil, and others. These display a strong relation and have a central place in the network of keywords (Figure 4). The results indicate that glyphosate, along with other herbicides, are broadly related with its intensive use in agriculture and they are associated to water pollution, derived, many times, from nonpoint pollution.

There is evidence that glyphosate is present in bodies of water, which may be a risk to aquatic life and human health, since concentrations have been found that are above the maximum permissible limit established by the European Union (Table 2). For the specific case of Mexico, there are five publications that evaluate the presence of this

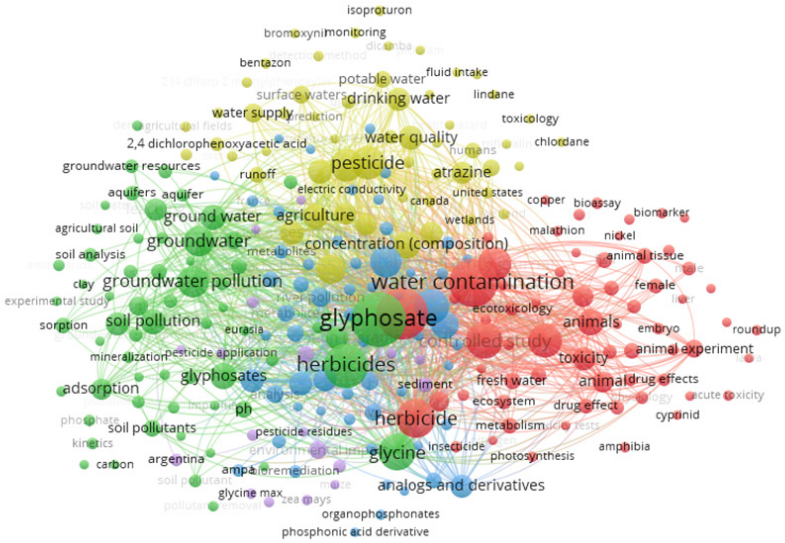

Figure 4. Network of co-occurrences of keywords focused on water pollution with glyphosate.

Table 2. Occurrence of glyphosate in water resources worldwide.

Country	Matrix	DF (%)	C (µg L)	MPL† (µg L)	References
European Union countries	Surface water Underground water	28.9 1.3	<0.003–50 <0.01–24	0.1 0.1	Horth and Blackmore, 2009.
Mexico	Surface and underground water	100	0.13–36.7	0.1	Ruíz-Toledo and Sánchez-Guillen, 2014.
United States	Various types of water	39.4	<0.02–476	0.1	Battaglin *et al.*, 2014.
Mexico	Drinkable bottled water	86.7	<0.05–0.78	0.1	Rendón-von Osten and Dzul-Caamal, 2017.
Mexico	Bottled, surface and underground water	63.8	0.1–4.3	0.1	Reynoso-Camargo *et al.*, 2020.

LMP: maximum permissible limit; DF: detection frequency; C: concentration. †European Union (*Council of the European Union*, 1998).

contaminant in bodies of water. However, findings are alarming, since the compound has not only been found in surface water, but also in bottled water and in underground public water supplies, mainly in locations far from urban areas (Rendón-von Osten and Dzul-Caamal, 2017; Reynoso-Camargo *et al.*, 2020**).**

The presence of glyphosate in the surface water of rivers and lakes, as well as in underground waters, is due to the leaching of this compound in the soil due to rains

or the irrigation of agricultural fields, due to the property of this herbicide being highly water-soluble (González-Ortega and Fuentes-Ponce, 2022). Mörtl *et al*. (2013) observed this effect in surface and underground water samples taken in different sites in Hungary, and found greater concentrations in surface and underground water samples during the rainy season in Bekés County, which is characteristically a region with an intensive agriculture, whereas in surface waters of the Danube river in the dry season, relatively low concentrations were registered. Battaglin *et al*. (2014) pointed out that the concentrations of glyphosate are related with the increase of their use, mainly in transgenic crops such as soybean, cotton and maize.

The concentrations of glyphosate and metabolites in the bodies of water have a close relation with the location of agricultural fields, the type of agriculture (high- or low-input), rainfall and the characteristics of the catchment area. All this, as a whole, determines the amount of glyphosate that reaches the bodies of water and therefore the degree of pollution. Coupé *et al*. (2012) pointed out that the watersheds that are most at risk due to the transportation of glyphosate are those with higher rates of application and rainfalls that result in surface runoff.

CONCLUSIONS

The studies related to the presence of glyphosate in bodies of water, in foods and its impact on human health have increased worldwide. In the last ten years (2011–2021) the number of publications tripled in comparison with 2010. Out of the 1607 references published around the world from 1980 to 2002, Mexico only participates with 1.8 %, represented by publications related to toxicity in foods, human health and the biota (83 %) and the pollution of bodies of water (17 %). However, despite the prohibition of the use of glyphosate in agriculture being a national priority, there are still few studies carried out on the topic and on its potential effect on the environment and health.

Out of the network of co-occurrences of keywords, the words that were found to appear most frequently were glyphosate or Roundup® and its relation with toxicity, pollution, agriculture, surface water, underground water, drinkable water, soils, fish, amphibian, humans and laboratory animals. Since glyphosate is a water-soluble compound, it has the ability to quickly pollute bodies of water. Its presence is broadly related to agricultural fields, the use of inputs, the amount of herbicide applied and rainfalls. Finally, an increase in scientific research is necessary, with emphasis on bodies of water and the water resource, which is crucial to guarantee food security, as well as scarce and overexploited.

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