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Regeneration and sustainable chemistry: Current dynamics, interconnections, and perspectives

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This paper aims at exploring the role of sustainable chemistry to address regenerative practices, dynamics, and systems as the ones related to agriculture, food production, and processing, including topics such as valorization of agro-industrial waste, biorefinery, biomass, bio-based materials and related flows or processes, renewable resources and energy, considering the links to the United Nations Sustainable Development Goals.

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Introduction

Among the initiatives aiming at a fairer and healthier present and future, sustainable chemistry (SC) has stood out in various fields and social sectors due to the fundamental role of chemistry in achieving this goal. SC seeks to incorporate advances from other fields, including solutions that don't involve chemical processes when they can potentially offer a sustainable alternative to current products and services [1,2]. Recently, it has become more evident the connections of SC with the concept of regeneration through an ecological, integrative, and holistic perspective [3]. Although the understanding of sustainability has advanced in recent decades, it still relies on a predominantly anthropocentric and technical approach to addressing socio-environmental problems, focusing efforts on symptoms rather than on the causes responsible for the transgression of planetary boundaries [4–7].

Considering that food production is one of the main sources of pollution and is insufficient to meet the growing demands of the global population [8], sustainable chemistry, alongside advances and solutions from other fields—such as regenerative systems—can help guide the processing of food materials [8,9]. According to the literature, there is an expanding number of works that relate sustainable chemistry to agriculture, mostly to regenerative agriculture.

Starting point

The concept of regeneration has become familiar in discussions about sustainability more recently [4,5] and, even though still, it is possible to find connections between them in the literature in different scientific areas, including chemistry [3], and social areas – from economies to cities [3,6].

Regeneration (from the Latin verb *generare*) means to generate or give birth, and it represents an internal movement of renewal or recreation toward a desired result [3]. A regenerative dynamic exists when results are continuously perpetuated, producing constant or increasingly higher levels, without external negative effects; it refers to a system with endogenously self-perpetuating results in a mutualistic perspective with other systems [3,6].

Following an extensive literature review, Buckton et al. (2023) conceptualized these systems through a regenerative lens based on five elements: an ecological vision, with humans coevolving alongside nature; mutualism; reflexivity; a high diversity of physical, ecological, and human components; and agency [6]. The regenerative lens is useful for outlining other values and worldviews, especially when we analyze systems from the outlook of restoration which, in its etymological origin, expresses repairing, giving back, or building a new [3,6]. In other words, it is a one-way process from humans to nature—in essence, separated. From this viewpoint, the recovery of degraded forests through tree planting would only be considered regenerative if it were capable of self-perpetuating in a relationship of internal and external balance, thereby improving the physical, ecological, and social aspects of the ecosystem.

Thus, we can consider that every system needs an external effort to initiate a regenerative process, but it will only become effective as such if it internally achieves a certain level of autonomy in relation to the conditions that maintain it [3]. The limitations may include factors associated with climate, sunlight, weathering, human action, among others, suggesting the existence of different dynamics that feed back into each other with a common goal: life [3,6].

Understanding sustainability apart from the concept of regeneration would be, in our view, merely a restorative practice because it is mostly based on remediation, with exogenous and technical actions (specific or not) that will not always be sufficient for the internal autonomy of the system and its consequent effect on the surroundings [4,6]. Looking at sustainability through a regenerative lens [6], on the other hand, allows for the complement of the purely restorative vision and the creation of a new political *ethos* for thinking, acting, and relating co-evolutionarily with the physical, natural, and human worlds [4–6].

We can consider that, among the five elements based on a regeneration perspective [6], the agency represents a more internal, individual movement (even if it also depends on factors external to the individual), oriented toward intentional action. Based on the agency, Fischer et al. (2024) defined the term regenerative practices as a set of systematically organized, nonspecific activities (whether in terms of energy or other resources) that support regenerative dynamics [3]. According to the authors, regenerative practices have four principles: 1) a practical understanding of how regenerative dynamics work; 2) rules to guide actions; 3) a teleoaffective structure for guidance; and 4) an understanding of regeneration and regenerative practices [3].

Often in the opposite way, conventional agriculture has key critical points [3], such as the use of large amount of synthetic chemical compounds and several processes that can cause more damage than others, considering the extensive use of water, land, and high greenhouse gas emissions. These key points have driven research and related activities in the field of chemistry, which are fundamental in creating interconnected and regenerative solutions for food production and consumption [9]. In this context, the main objective of this work is to outline the possible paths for regenerative practices in agriculture, understanding the developments in green and sustainable chemistry as a set of activities aimed at achieving this. By delimiting the writing within these four principles for regenerative practices, we seek to understand the functioning of these food systems through a review of the literature from the last two years.

Sustainable chemistry and regenerative agriculture: a call to action

A literature search over the past two years was conducted using Clarivate's Web of Science database and a combination of terms (regenerative agriculture, sustainability, sustainable chemistry, and green and sustainable chemistry). The selection of articles enabled grouping them into different contexts representative of regenerative practices (Table 1).

Table 1

Articles related to the fields of green and sustainable chemistry and regenerative agriculture.

Categories	Articles
Bio-based materials	[10–22]
Repurposing agro-industrial waste	[23–33]
Technologies and resources	[34–39]
Concepts	[3,40–43]

Regenerative agriculture seeks to improve soil health or restore it, as well as improving life and diverse biological processes in soils, carbon content, and the ability to filter and retain water [3]. Specific actions include maximizing the time crops covering the soil, increasing crop diversity in space and time and minimizing soil disturbance. Regenerative dynamics represented by the introduction of bio-based materials in agriculture permeate the entire cultivation cycle, from the use of biostimulants for seed germination to pest control carried out by natural and sustainable substances. Aligned to these concepts, Li et al. (2024) describes the discovery of potential biomolecules that contribute to crop growth, restoration, and soil health [17]. Chemical knowledge combined with other scientific fields is essential at all stages for the discovery of biomolecules with bioactivity (identification, extraction and isolation, determination of bioactivity and active compound(s), elucidation of mechanisms, and formulation and evaluation of efficacy) [17]. Specifically in the extraction stage, Lalruatfeli et al. (2024) highlight the use of natural liquids, such as water and cow urine, to replace conventional solvents in the extraction of seaweed biocomposites, which have the potential to promote seed germination [16].

The application of regenerative practices in agricultural ecosystems through the incorporation of bio-based materials has been evaluated in various studies [13,22], including research developed under unfavorable irrigation conditions, where plants exhibited greater resistance [21]. The effectiveness of fertilizer produced from a mixture of orange agro-industrial waste, sulfur, and bentonite was assessed in the study by Marra et al. (2024), which reported a 15 % increase in soil microbial biomass, total phenolic content, cations, bacterial colonies, and enzyme activities, with effects varying depending on soil characteristics [18].

Slow and controlled release fertilisers synthesized from renewable biopolymers are highlighted in Firmanda et al. (2023), in which nutrients are incorporated into a matrix based on biopolymers to design nutrient release kinetics [15]. Nanosystems also favour these processes by improving adhesion, stability, and the ability to release the compounds, even reducing the need for reapplication of the formulation [20]. Rodrigues et al. (2024) used lignocellulosic biomass to formulate nanopesticides, highlighting its potential as a sustainable alternative to conventional pesticides [20]. Another aspect refers to the use of fertilizers based on free amino acids from agro-industrial waste (byproducts of greaves and polluted water), which are promising for stimulating plant growth, improving productivity, and reducing dependence on synthetic fertilizers [19].

Considering that the byproducts generated by the agro-industrial sector represent a growing challenge, their transformation into valorized compounds with varied applications is consistent with sustainable principles [28]. The production of essential oils, for example, generates a large amount of waste and/or byproducts as more than 95 % of aromatic and medicinal plants are left as residual biomass after distillation [23]. Other studies have also investigated the bioactive compounds present in walnut and elderberry byproducts related to human health and the protection of agricultural crops [30], as well as the development of biopesticides obtained from tomato waste [31].

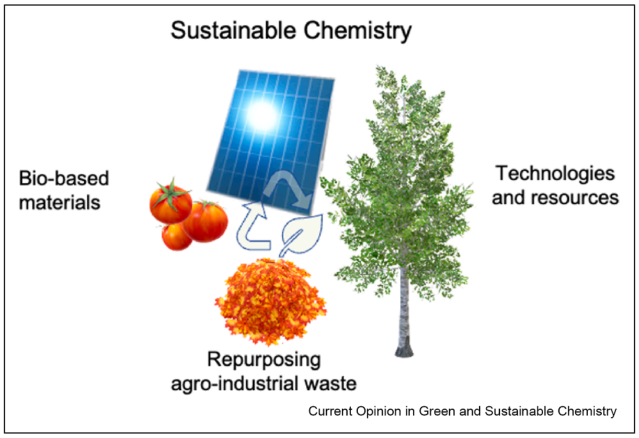
Poccienne et al. (2022) emphasize the potential of agro-industrial waste for a circular economy. The authors argue that the byproducts generated in the final processing of buckwheat (a common food ingredient) can be returned to the soil to replenish nutrients, as well as being used as a raw material for granular biofuels [29]. Li et al. (2023) also underline the production of energy through biomass derived from the lignocellulose of *Staphylea holocarpa* wood. In addition to energy from biomass, biosorbents obtained from agricultural waste have shown promise for wastewater treatment [24].

The sustainability of different materials used in agriculture and beyond cultivation was questioned by Gamage et al. (2022) [26]. The authors discuss the use of biodegradable polymers and renewable sources for various agricultural applications to replace conventional ones, highlighting the underutilization of agro-industrial waste sources of starch and, on the other hand, their potential as a raw material for different materials (pipes, nets, packaging, etc.) [26]. The interdependence between the production of biomaterials in agriculture to obtain biomass and return nutrients was studied by Stathatou et al. (2023). The authors analyzed an agricultural center located in Michigan, USA, which faces environmental degradation, revealing mutual benefits through a synergistic link between the agricultural and human ecosystems [32].

With regard to technologies and resources, we underline possible solutions for food production that involve the use of biotic systems (e.g. fungi) and artificial processes developed from a sustainable perspective, such as nanotechnology [38]. Venâncio et al. (2024) describe the metabolic and biochemical processes carried out by fungi in the degradation of plastic particles, indicating the role of microbiota in soil resilience, as well as in solving the problem of plastic particle accumulation in edible plant parts [39]. Behrooznia et al. (2024) discuss applications and extraction methods for sustainable polymers (chitosan, cellulose, starch, among others) to obtain hydrogels and nanocomposites applicable in agriculture, biomedicine, and food packaging [34]. Liu et al. (2024) developed a polysaccharide-based hydrogel structure for cultivating microalgae, achieving a higher yield per unit of water consumption compared to traditional methods [36]. In addition, technologies that make it possible to estimate soil organic carbon and nitrogen rates were described by Mahmud et al. (2024), considering that analyzes commonly carried out in the laboratory can be limited to remote areas and when there are a large number of samples, making it difficult to plan and monitor agricultural systems [37].

Finally, the articles categorized as concepts generally describe the relationship between green and/or sustainable chemistry and a more environmentally and socially beneficial food production system. Gupta et al. (2024) explore the transformative impact of green chemistry on agriculture, food processing, and waste management [41], while Sharma (2022) proposes 12 principles of sustainable agriculture inspired by the 12 Principles of green chemistry [42]. A connection between the circular economy and agriculture is made by Toplicean et al. (2024), pointing out ways of using biomass, the problems faced by plastic recycling, and the role of the circular economy in mitigating climate change and biodiversity loss [43]. Vicente et al. [44], when discussing new responsive deep eutectic solvents and their role in sustainable chemistry, also highlighted that the main challenges are connected to the creation of circular bioeconomy models that are designed to be regenerative, so that products, components, and materials always retain their maximum utility and value, rather than relying solely on end-of-life solutions. The collective and ongoing efforts between different scientific and social fields to prioritize and implement regenerative practices, including the training and continued education of professionals, leaders, and policymakers engaged in the urgent transformations are also emphasized in the literature [40]. Figure 1 shows the main connections found and related to regenerative practices, in the context of material circularity and processes in the field of sustainable chemistry for more sustainable, nutritious, safer and

Figure 1



Key elements interrelating sustainable chemistry with regenerative practices regarding material circularity and processes for the development of sustainable food systems.

accessible food production, consumption, management, and education.

It is interesting to note that the regenerative practices and dynamics described in the literature are mainly related to agriculture, in the mode of crop production, but some more recent studies have considered food processing, which transforms raw foods into products such as concentrated orange juice and its byproducts, which are seen as coproducts with high added value. In addition, food prepared by consumers, food outlets, and restaurateurs, whose non-committable waste could also be reintroduced into the food chain in a regenerative manner [45].

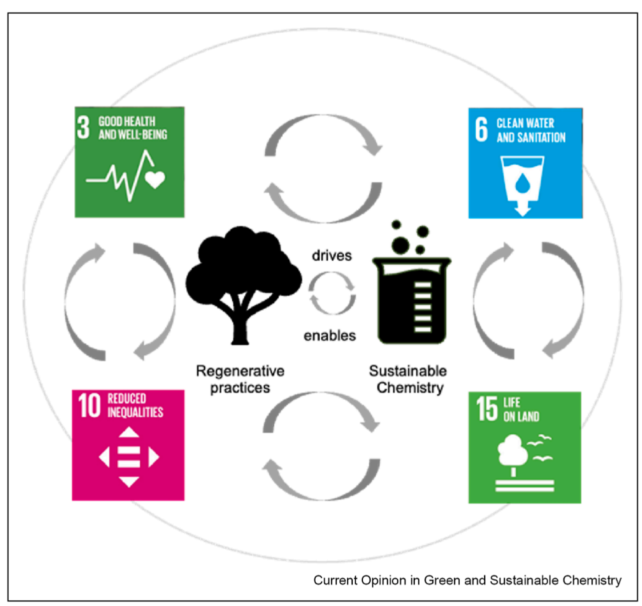
Interconnections and perspectives

In this work, central aspects related to sustainable solutions in the field of agriculture, regenerative practices, dynamics and systems, food production and processing were analyzed, including topics such as valorization of agro-industrial waste, biorefinery, biomass, bio-based materials and related flows or processes, renewable resources and energy, considering the links to green and sustainable chemistry and the United Nations Sustainable Development Goals (UN SDGs). As noted in recent literature, green and sustainable chemistry plays a central role in promoting regenerative practices and dynamics, with great future potential especially toward more sustainable food systems.

Chemical knowledge, when guided by regenerative principles, enables the creation of self-sustaining systems that generate multiple and lasting benefits. The role of green and sustainable technologies is fundamental, particularly in developing biodegradable materials, biofertilizers, and circular economy systems that align with natural cycles and promote the regeneration of both physical and human ecosystems. This underscores the need for public policies and strategies that encourage the adoption of regenerative practices. Collaboration among scientists, farmers, policymakers, and consumers is essential to transform conventional production systems into regenerative, circular, and equitable ones. We also emphasize the importance of integrating chemistry with ecological, social, economic, and ethical knowledge to foster a systemic approach to sustainability challenges.

The UN SDGs cannot be addressed as fragmented or independent targets. Instead, they need to be approached from a regenerative perspective, which recognizes the interdependence between systems and their ability to feedback loops into each other in an integrated way. A regenerative practice goes beyond mere preservation or damage restoration but seeks to actively create conditions that favour life, in a continuous cycle of renewal. In this context, the UN SDGs must be interpreted holistically, as progress in one goal catalyzes advancement in others, while imbalance in a single goal destabilizes the others. For example, it is not possible to guarantee health and wellbeing (SDG 3) without considering access to drinking water (SDG 6), the protection of biodiversity (SDG 15), the reduction of inequalities (SDG 10), and beyond (Figure 2). Regenerative practices make it possible to perceive

Figure 2



Regenerative practices and sustainable chemistry approaches and their interconnections with the SDGs, highlighted as SDGs 3, 6, 10, and 15.

these connections and design solutions that favour the autonomy of systems and their ability to maintain and develop from within, in synergy with others. This calls for a new political *ethos* that prioritizes coevolution among physical, human, and natural environments—one that recognizes how our actions must foster not merely survival but the vitality of the systems we inhabit. Such a paradigm shift enables us to build a present and future that not only remedies past harms but actively regenerates the planet's physical, ecological, and social foundations.

In this context, sustainable chemistry plays a central catalytic role in this transformation since it enables self-sustaining systems that generate multidimensional and long-term benefits [46]. For instance, by developing energy-efficient processes and products aligned with natural cycles, sustainable chemistry can disrupt linear, extractive models and fosters a circular, regenerative economy and practices that foster the development of life-centered materials and technologies based on collaboration and coevolution. Sustainable chemistry, especially regenerative agriculture and food processing, contribute to preventing and reducing socio-environmental impacts, also building resilient food systems capable of regenerating soils, preserving and improving biodiversity, and empowering community, locally and globally.

Author contributions

V.G.Z.Z.: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing. C.J.C.G.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing — original draft, Writing — review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL Write in order to review the English language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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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Data availability

Data will be made available on request.

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Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

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