Biopesticides for Sustainable Agriculture

Subjects: Agronomy

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Biopesticides are organisms or natural formulations that control or eliminate pests via diverse modes of action (MoA). They cover a wide range of organic products and formulations, such as predatory and parasitic species, biochemical compounds (and their chemical equivalents), and plant-incorporated protectants (PIPs). Biopesticides play critical roles in agriculture, which is the frontier sector driving the Sustainable Development Goals (SDGs). Apart from controlling agricultural pests and diseases, they are friendly to the environment, benign to beneficial organisms such as pollinators and plant growth-promoting microorganisms, promote crop productivity and are sensitive to resistant pests created by synthetic pesticides. In addition, biopesticides are very much compatible with the integrated pest management system, which only admits synthetic pesticides as a last resort. As organic formulations, biopesticides fit the defining criteria of Green Chemistry in that they are safe products synthesised from renewable substrates, produce non-toxic compounds and can be driven by minimal energy and biocatalysts.

bio-controlling agents biofertilizers crop diseases green chemistry organic formulation pests pollinators SDGs synthetic pesticides

1. Biopesticides' Definition and Suitability as Green Chemistry Agents

Organic extracts from shells, crustaceans, and algae function as signal molecules to trigger a defensive response in plants and animals, producing long-lasting effects against biotic infections. These substances are known as semiochemicals [1][2]. So, biopesticides include semiochemicals and biochemical analogues. However, if an organic product exerts its toxicity on pest neurological systems, it becomes a poison [3]. Based on this criterion, rotenone, nicotine, sabadilla, and pyrethrins are regarded as poisonous substances even though they are effective botanicals [4]. As green compounds, biopesticides are of great interest to the 12 Green Chemistry Principles (GCPs).

The overarching 12 GCPs were articulated by Anastas, P. and Warner, J. C. in 1998. These principles are the universal gold standard for developing environmentally friendly processes and products (**Figure 1**). Green Chemistry advocates methods that lessen the use of dangerous substances and minimise the development of toxic intermediates during chemical transformations. The 12 GCPs require that products are made from renewable feedstock (the focus of Principle 7) under the following conditions:

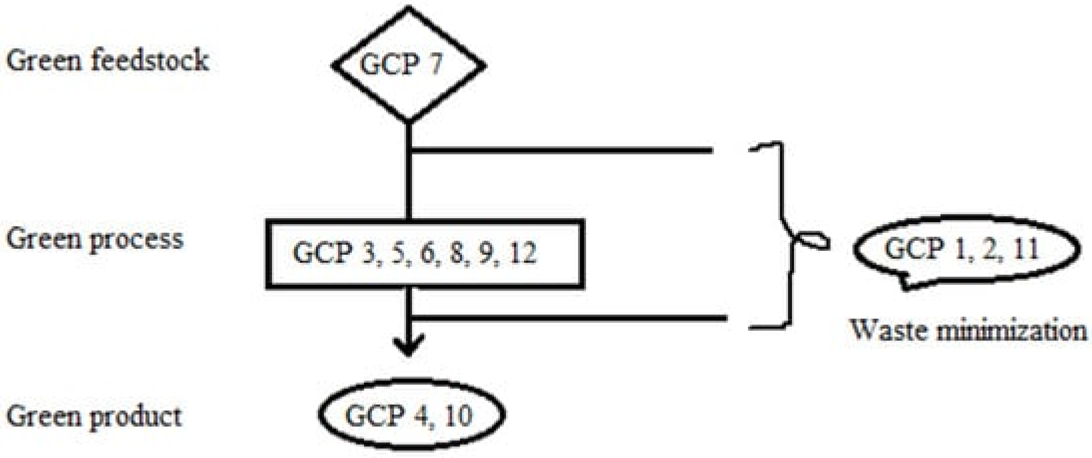

Figure 1. A simplified presentation of the production of a green product concerning the 12 Green Chemistry Principles (GCP). GCP 7: Renewable feedstock; GCP 3: Less harmful chemical synthesis; GCP 5: Benign solvent and auxiliary; GCP 6: Energy efficiency; GCP 8: Reduce derivatives; GCP 9: Catalysis; GCP 10: Degradation design; GCP 12: Inherently safer process; GCP 4: Safer chemical design; GCP 10: Design for degradation; GCP 1: Waste prevention; GCP 2: Atom economy; GCP 11: Real-time analysis.

- Synthetic processes are safe, green, and use minimal energy;
- The final products are environmentally friendly;
- Wastes are prevented or minimized.

According to Fenibo et al. [5], the first condition is connected to the 3rd, 5th, 6th, 8th, 9th, and 12th GCPs. The second condition is addressed by Principles 4 and 10, while Principles 1, 2 and 11 ensure waste prevention and minimization (condition three). The surest means of securing condition three is to ensure that the starting materials are integrated into the finished product [6]. As a green product, biopesticides are effective at low concentrations, biodegradable, and harmless to non-target biota. The use of reductases, transaminases, oxidases, hydrolases and other biocatalysts not only meets the minimum energy requirement but also benefits the environment and the economy. In this sense, biopesticides align with green technology and SA. The latter is characterised by the responsible consumption of resources, biodegradability, and productivity [7]. One important outcome of resource consumption in agriculture is the eradication of pests, as shown in **Table 1**. The conscious attempt to maintain these sustainable attributes implies integrating green chemistry principles into agricultural practices that previously relied on synthetic pesticides (SPs) for pest eradication.

Table 1. Notable examples of plant pests.

Pests	Hosts	Impact	Reference
Weeds: Annual: *Ambrosia artemisiifolia, Abutilon theophrasti, Chenopodium album* (Baconweed), *Amaranthus* spp.	Varieties of crops including grains, wheat, rice, maize, beans, chickpeas,	• Reduces sunlight to crops;	[8][9][10][11]

Pests	Hosts	Impact	Reference
(Pigweeds), *Digitaria* spp. Biannual: *Ailanthus latissimus* (Tree-of-heaven), *Cirsium vulgare (Bull thistle),* Perennial: *Convolvulus arvensis, Rubus* spp. (Blackberries), *Smilax* spp. (Greenbrier), *Phytolacca Americana* (Pokeweed), *Toxicodendron radicans* (Poison Ivy).	potatoes, vegetables, and cotton.	• Aggressively competes for water and nutrients; • Tends to grow faster than crops and crowd out actual crops; • Can produce certain chemicals that are toxic to crops or grazing animals.	
Nematodes: *Heterodera* spp. and *Globodera* spp., (Plant-parasitic nematodes (PPN), *Meloidogyne* spp. (root-knot nematodes), *Pratylenchus* spp., *Heterodera* and Globodera spp. (cyst nematodes), *Bursaphelenchus xylophilus* (pine wilt nematode), *Aphelenchoides besseyi, Radopholus similis* (burrowing nematodes), *Xiphinema index* (virus vector nematode), *Ditylenchus dipsaci*, *Nacobbus aberrans, Rotylenchulus reniformis* (reniform nematode).	Varieties of crops including peaches, nectarines, tomato, pepper, cucumber, almonds, squash, eggplant, okra, sugarcane, beetroot, and pineapple.	• They attack plant roots and other below-ground parts and sometimes manipulate gene regulation and metabolism to their advantage; • They also attack stems and leaves reducing photosynthetic and water and nutrient translocation.	[12][13][14]
Insects Aphids, Mexican fruit flies (*Anastrepha ludens*), grasshoppers, whiteflies, spider mites, silkworms, desert locust (*Schistocerca gregaria*), migratory locust (*Locusta migratoria*), screwworm fly (*Cochliomyia*), tsetse flies (*Glossina*), uzi fly (*Exorista bombycis*), potato beetle, Banana- spotting bug (*Amblypelta lutescens*), European corn borer (*Pyrausta nubilalis*), Japanese beetle (*Popillia japonica*), alfalfa weevil (*Hypera postica*), alfalfa aphid (*Therioaphis maculata*).	Varieties of crops including sugar beets and potatoes, maize, peanuts, chickpeas, and cotton.	• They cause both direct and indirect injuries to growing crops; • Direct injury is caused by the insects eating the leaves, reducing photosynthetic activities and burrowing holes in shoots and stems which reduce nutrients and water translocation, burrowing holes in fruits and or/roots, thereby reducing product quality.	[15][16][17]

Pests	Hosts	Impact	Reference
Small vertebrates: Field mice, house mice, rats, feral cats, bats, foxes, wild dogs, pigs, rabbits, snakes, dogs, pigeons.	Varieties of crops including potatoes, grains, sugar beets, citrus and succulent fruits, peaches, plums, pears, strawberries, grapes, potatoes, and carrots.	• Bites on fruits and root crops are entryways for pathogenic and spoilage microorganisms; • Their excrement and urine on food could be a source of poisoning and diseases; • Cause injury and kill cultivated plants.	[18][19][20]
Fungi *Pythium* and *Phytophthora infestans* (Fungal-like organisms), *Fusarium* spp., *Fusarium graminearum, Fusarium oxysporum, Rhizoctonia solani*, *Tilletia* spp., *Plasmopara viticola, Puccinia graminis* var. *tritici, Gaeumannomyces graminis* var. *tritici, Blumeria graminis, Mycosphaerella graminicola, Botrytis cinerea, Ascosphaera* spp., *Ustilago maydis, Aspergillus* spp., *Magnaporthe oryzae, Puccinia* spp., *Colletotrichum* spp., *Sclerotinia sclerotiorum, Verticillium dahlia, Armillaria* spp., *Melampsora lini*, *Phakopsora pachyrhizi Blumeria graminis.*	Variety of crops including grains, rice, wheat, sorghum, potatoes, cassava, tomatoes, bananas, cucumber, grapes, strawberries, coffee, cacao, spices, mangos, and several nuts.	• Fungi play converse roles of being pathogenic agents of diseases and some species are used as biopesticides; • Destruction of mature and senescent tissues of dicots including stored grains; • The growth of fungi on crops, fruits and tubers causes spoilage in the form of seedling damping-off, chlorosis, wilts, rots, rust, brown spots, black spots, smuts, mildew and dusty powder.	[21][22][23]
Protozoa: *Phytomonas leptovasorum, Phytomonas stahelii, Phytomonas françai, Phytomonas serpens*	Variety of crops including, coffee beans, Coconut palm, oil palms, cassava, tomatoes.	• These protists can cause phloem necrosis, hampering the transport and distribution of organic nutrients in plants. Visible symptoms are yellowing,	[24][25]

Pests	Hosts	Impact	Reference
		drooping leaves, foliage desiccation, root die-back and eventual death of the tree.	
Bacteria: *Xanthomonas campestris, Psuedomonas syringae, Pseudomonas corrugate, Clavibacter michiganensis, Pseudomonas* spp., *Erwinia* spp., *Ralstonia solanacearum, Rhizomonas suberifaciens, Erwinia carotovora, Agrobacterium tumefaciens, Spiroplasma citri*	Variety of crops including, lettuce, cucurbits, cucumber, pumpkin, melon, tomatoes, chilli, potatoes, eggplant, rice, beans.	• Bacterial infection occurs at points of injury on plants and is aided by free water; • They cause a variety of symptoms including, scabs, blights, soft rot, lesions, wilt, cankers, discolouration, disagreeable odours, and necrosis on infected areas.	[26][27]
Viruses: Cassava mosaic begomovirus, Citrus Tristeza closterovirus, Barley yellow dwarf luteovirus, Plum pox potyvirus, Potato leafroll polerovirus, Cacao swollen shoot badnavirus, Potato potexvirus X, Tobacco mosaic tobamovirus, Turnip crinkle carmovirus, Tomato spotted wilt virus, Cucumber green mottle mosaic virus, Pepino mosaic virus	Variety of crops including, cassava, citrus fruits, barley, cucumber, lettuce, tomatoes, peppers [31]	• Viruses can initially be symptomless, or their symptoms may resemble other diseases of known aetiology making it difficult to differentiate and treat; • Some observable symptoms include chlorosis, mosaic leaf pattern, crinkled leaves, and yellowed leaves.	[28][29][30]

s of these od as the ulace and . Some of s. Beyond ding plant plants for mutual benefits. Plants benefit from the essential nutrients supplied by the microorganisms, which in turn gain energy and protection. In some cases, these rhizomicrobes (rhizobacteria) antagonise soil pests using bioactive substances they produce and metabolise carbon-rich pollutants as an energy source [32]. The majority of these growth-promoting rhizobacteria (PGPR) perform nitrogen fixation, mineral solubilization, generation of active metabolites, and induction of systemic resistance for the advantage of the concerned plants [33]. The assimilation of H_2 during nitrogen fixation improves the growth of the associated plant [34]. Examples of PGPR (biofertilizers) are *Azospirillum*, *Allorhizobium*, *Bacillus*, *Bradyrhizobium*, *Arthrobacter*, *Agrobacterium*, *Mesorrhizobium*, *Caulobacter*, *Rhizobium*, *Azotobacter*, *Frankia*, *Erwinia*, *Micrococcus*, *Serratia*, and *Flavobacterium* [35]. Inoculation of PGPR to plants improves yield, and as a practice is becoming popular. The use of biofertilizers (PGPR) and biopesticides is essential to organic farming, conserves biodiversity and increases crop yield.

An increase in crop yield is partly attributed to insect pollination. Pollinators contribute to more than 75% of food crops, and 90% of wild angiosperms found in agro-fields benefit from most insect–plant interactions [36]. In addition, the interaction between pollinators and plants results in genetic variability, yield stability, early reproduction, and strong traits [37]. Adamidis et al. [38] established that honeybee-driven pollination contributed to a yield increase in sesame and cotton by 62%. Other significant pollinators are solitary bees, bumble bees, moths, and butterflies. Studies have shown that pollination services raise crop value by USD 17,174 per hectare, boost worldwide food production by 9.5%, with a net worth of USD 405 billion, and account for 67% of Tanzania's food crops [39][40]. Apart from food, pollinators also contribute to the production of timber, biofuel, fibre, and medication [41]. Garratt et al. [42] noted that the gains from pollination services can only make sense where fertilisers are not limited. This implies that in the presence of sufficient plant nutrients (biofertilizers) and thinned pests, the many advantages of pollination can be fully realized.

From the preceding sections, it is clear that pests, nutrients, and pollinators are critical factors in agricultural practice. Water, the atmosphere, and humans are also critical factors in agriculture. The involvement of pesticides (biopesticides and SPs) improves agro-yield by mitigating pests. However, the other remaining factors respond differently to pesticides in general. Apart from their pest-controlling efficacy, SPs defile the air, soil, groundwater, and surface water. The polluted state of the environment normally leads to health challenges, the abandonment of natural resources, biodiversity losses, and high costs of remediation. Environmental chemical-instigated health challenges can lead to discomfort, fatigue, Parkinson's disease, cancer, or even death [43]. Attina et al. [44] revealed that the negative impact of organophosphate pesticides costs the United States USD 44.7 billion/year. Earlier, Nowak and Greenfield [45] estimated damages caused by SPs in the following sectors: bird losses (USD 2.2 billion/year), crop losses (USD 1.4 billion/year), public health (USD 1.1 billion/year), pesticide resistance (USD 1.5 billion/year), and groundwater pollution (USD 2.0 billion/year). The high degree of soil and surface water contamination leads to abandonment or suspension of usage until remediation is carried out. Chemical remediation can be accomplished through conventional and bioremediation approaches. Though the bioremediation approach is considered the best option, both techniques cost money, time, and effort. The attenuation of a particular pesticide to a safer target level usually requires a period of 12 to 24 months. All these costs and negative effects of using SPs in agriculture could be avoided by utilising biopesticides instead. The application of biopesticides provides a safer environment and improves productivity. These are areas of concern for the sustainable development goals (SDGs).

The SDGs address 17 subject areas, poverty (SDG1), hunger, health, education, gender, clean water, energy, economic growth, infrastructure, inequality, communities, production and consumption, climate, life underwater, life on land, strong institutions and partnership (SDG 17) [46]. However, the ones that are of interest to agriculture are life under water (SDG 14) and on land (SDG 15). Each of them serves as a base for agricultural activities. Land, especially fallowed ones, can be cultivated while water bodies can be used for aquaculture for subsistence and commercial farming. Sustainable agriculture (SA) is driven by the conscious utilisation of water (SDG 6), nutrients, and energy (SDG 7) [47]. Agriculture-based skills and education (SDG 4) and responsible production of agro-products and consumption (SDG 12) optimise the impact and services that SA provides. Examples of services agriculture provide are the reduction of poverty (SDG 1), drastic hunger reduction (SDG 2), nutrient-linked health improvement (SDG 3) and the reduction of global warming (SDG 13) [48]. Vegetation helps reduce greenhouse gases by absorbing CO_2. For this reason, research on CO_2 capture and sequestration has been given priority attention in recent times to address global warming [49]. Strong institutions (SDG 16), which promote policies, peace, and justice, serve as enablers of SA improvement and support practitioners on an equal gender basis (SDG 5) to engage in agriculture as a decent profession for economic growth (SDG 8). In summary, it is instructive to conclude that SA platforms (SDG 14 and 15) provide services such as hunger eradication (SDG 2), poverty reduction (SDG 1), health improvement (SDG 3), and air purification (SDG 13). These services can be optimised by ensuring education (SDG 4) and judicious production and consumption (SDG 12) habits. Strong institutions serve as essential elements for all aspects. Conclusively, biopesticide-driven large-scale agriculture is linked to 11 of the 17 SDGs and guarantees food security, productivity, and environmental sustainability.

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