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Review

Microalgae-Based Crop Support Technologies Show Multifaceted Promise Well-Suited to Looming Threats

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Abstract: This review summarises the available evidence on the prospects for using microalgae or their extracts to support crop production. The evidence is limited but suggests technological promise in several distinct ways, namely, higher core productivity, enhanced resilience to biotic and abiotic stresses, and better-quality produce. The different efficacy pathways of these microalgal technologies were examined to assess their scope to help address key farmer priorities. Their scope to help farmers face climate change and land degradation was a particular focus, given the magnitude of these threats. These microalgal technologies are framed in terms of their pertinence to farmer priorities due to the centrality of farmers to food systems. Notably, farmers' technology adoption decisions are key to food system outcomes. The findings reported suggest that these crop support technologies could potentially deliver major benefits to farmers, consumers, and the environment. For the moment, however, this emerging literature remains largely neglected. Possible reasons for this are considered, as are potential ways forward. The review focuses particularly on the two most researched and widely available microalgae, the genera *Arthrospira* and *Chlorella*, in the interest of highlighting options farmers could adopt rapidly while research on the wider body of microalgae-based crop technologies continues.

Keywords: crop production; agricultural innovations; microalgae; nature-based solutions; climate adaptation; land degradation; food security; food systems transformation

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1. Introduction

Agricultural development has achieved great successes over recent decades, notably increasing productivity to sustain a growing population, yet these gains have come at a cost [1,2]. While food systems may superficially appear to be performing well, their hidden costs to society now total USD 12 trillion per year, which exceeds the world market for food system outputs. This includes (i) health costs linked to widespread obesity and malnutrition, as well as pollution [3]; (ii) economic costs of diminished productive potential due to unhealthy diets or malnutrition and destitution in farming communities; and (iii) environmental impacts like land degradation and climate change that undermine agricultural production. The future could prove dark unless such costs are tackled, with risks of widespread crop failures, while global priorities like the Sustainable Development Goals (SDGs) and Paris climate targets remain out of reach [1].

Leading voices have called for a food systems transformation to secure better outcomes for people and the planet [1,4,5]. Required transitions include practising productive yet regenerative agriculture, harnessing the digital revolution, and diversifying protein supply [6]. Such a transformation could powerfully boost food security and rural economies while fostering wider benefits, including healthier diets, climate mitigation, and biodiversity conservation. The economic gains to society could total USD 5.7 trillion per annum by

2030, based on addressing the hidden costs cited and creating new markets. It could yield 'exceptional returns on investment' while helping to achieve the SDGs [1].

Farms are the foundation of food systems but face growing risks, raising questions about their continued viability and the security of food supplies [7]. The costs of inputs like agrochemicals have tended to rise over time [8], which can limit their use and cause problems for farmers [9,10]. Climate change poses a grave risk to farming via dynamics like worsening heat and water stress or growing pest and disease threats [11]. Land degradation stemming from unsustainable land use can diminish crop productivity and heighten vulnerability to stresses, potentially leading to farms being abandoned [12]. Catastrophic falls in insect populations are another worry, given their role as pollinators [13,14].

In short, increasing shocks and stresses to agriculture threaten to disrupt food value chains and jeopardise food security. This has led to growing calls to improve their resilience, equity, and sustainability [15]. The question is how to deliver this.

Agricultural innovations that enable farmers to succeed despite such threats and help deliver sustainable food systems are urgently needed [16], since they can offer options for 'how' to achieve identified objectives, i.e., 'what'. Different analyses may, however, highlight different agricultural innovations. Some stress agricultural technologies that foster farming systems that are productive but also regenerative, such as agroforestry, bio-based inputs like biofertilisers and biopesticides, and data-driven farming [1]. Others focus on nature-based solutions, which aim to harness natural processes to address human challenges [17]. Still others focus on 'advanced' agricultural technologies like artificial intelligence, drones, and gene technology [18].

A recent high-level analysis of land management challenges emphasised combatting land degradation and desertification, delivering climate adaptation and climate mitigation, and ensuring food security [19]. It found that certain actions can simultaneously meet these multiple objectives while also contributing to the wider goals encapsulated in the SDGs. It noted that such actions can be grouped under different frameworks, including nature-based solutions, climate-smart agriculture, or agro-ecology [20]. This review employs the term nature-based solutions (NbSs).

Various NbSs are relevant to agriculture. They can deliver farm benefits like higher yields, resilience to stresses, and/or lower costs. Examples include conservation agriculture, incorporating legumes into fields or pastures, and seaweed-based feed supplements. Such NbS technologies can be effective, accessible, and affordable inputs to farming. They offer concrete pathways to transform farming systems by putting them on a regenerative and sustainable footing and could thus be key to securing ample, quality food supplies into the future [17].

NbSs hold particular promise for low-income countries, where farming represents 63% of jobs and 25% of GDP, vs. just 3% and 1% in high-income countries [1]. Early evidence suggests that the capacity of NbSs to boost yields is greatest in degraded and water-stressed areas, which include large swaths of Africa and South Asia [17]. NbSs could also be more accessible than conventional inputs, especially if they were grown locally, which could amplify their benefits to people and planet.

While NbSs can meet the needs of groups like farmers, they can also help deliver on societal aspirations. For instance, they can transform farms from drivers of wider problems like land degradation, climate change, and biodiversity loss to solution spaces for such issues [17]. Indeed, NbSs are sometimes framed primarily as a means to meet societal goals. For instance, the charity International Union for Conservation of Nature frames NbSs primarily as a means to address societal challenges. Emphasising their practical utility to specific groups could be important, however, particularly if their roll-out depends on adoption decisions by these users.

One emerging class of NbSs shows multifaceted technological promise as farming inputs, namely, those derived from microorganisms such as microalgae, bacteria, fungi, or viruses. Early studies suggest that such organisms or their extracts can support crop production by stimulating crop growth and quality [21–23], enhancing resilience to stresses [24–27], or controlling crop pests and diseases [28–30].

This class of NbSs could be called futuristic, given their multifaceted efficacy coupled with the inherent advantages of microorganisms. One advantage is their potential to reproduce rapidly, as illustrated by the 'explosive growth' of algal blooms [31], even costs of producing high-purity biomass remain an issue [32]. Another advantage is their scope to adapt rapidly via selective processes [33]. A third advantage is their suitability for modular production, which enables production across a wide range of localities or conditions [34].

One challenge is that the array of possibilities is daunting, given the vast numbers of species in these groups of microorganisms, making it hard for researchers to know where to focus. The available evidence on any given species and its possible technological applications therefore tends to be thin.

The present review focuses on one group of microorganisms, namely microalgae and cropping technologies based on them. This focus reflects the fact that established initiatives on technological applications of microalgae already exist, including international conferences and professional bodies. By contrast, the authors are unaware of similar initiatives focused on bacteria, fungi, and viruses. One exception is plant growth promoting rhizobacteria (PGPR), a family of crop inputs that is attracting growing attention. For instance, the "PGPR International Conference for Sustainable Agriculture" was just held for the eighth successive year [35].

Microalgae are a large group of mostly aquatic microorganisms that can be rich in nutrients and bioactive compounds. Estimates of microalgae diversity range from 200,000 to several million species, and they conduct half of global photosynthetic activity while also underpinning the food chain in many ecological niches [36].

The available evidence suggests that microalgae-based crop support technologies have broadly comparable efficacy to those based on other microorganisms, making them a worthy focus for research on using microorganisms for crop support.

This review focuses particularly on crop support technologies based on two types of microalgae, namely, the genera *Arthrospira* and *Chlorella*, which are also known as spirulina and chlorella (Figure 1). These are the two most studied, commercialised, and readily available microalgae, even if other microalgae like *Chlamydomonas* are also attracting attention from researchers. Technically speaking, *Arthrospira* are classified as cyanobacteria, but they are often grouped together with microalgae due to their similarities. This simplifying usage is observed in the academic [37,38], policy [39,40], and popular [41,42] literatures. The present paper follows this usage.

While often sold as food supplements, the evidence to date suggests that *Arthrospira* and *Chlorella* can also be effective as crop inputs. Notably, they compare favourably with other microalgae in their efficacy as crop support technologies. These two microalgae are also relatively inexpensive when bought in bulk (EUR 15.25 and EUR 24.95/kg, respectively [41]).

The net effect of these characteristics is that any agricultural technologies based on these two microalgae could offer scope for wider uptake by farmers in the coming years. Innovations like this that could be rapidly scaled up could offer early solutions to pressing problems with agricultural productivity and the continued viability of farms.

This paper reviews the available evidence on the scope for microalgae-based inputs to support crop production, notably given the looming threats from climate change and land degradation. It finds that these inputs have great potential to help farmers in several distinct ways, namely, by boosting yields, enhancing resilience to biotic and abiotic stresses, and improving crop quality.

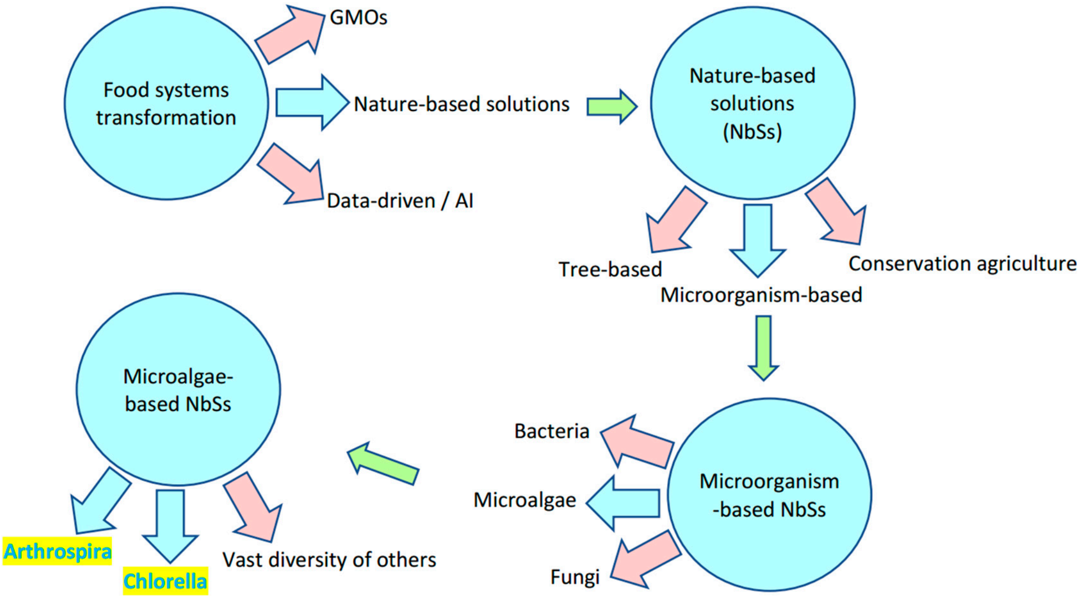

Figure 1. Agricultural innovations to help deliver food systems transformation, including the focus technologies.

2. Materials and Methods

The present analysis is framed around farmers' priorities. This follows from the fact that farmers function as CEOs of their farms, managing them based on perceived advantages [1]. As such, they are central to food system outcomes. Farmers' choices regarding agricultural technologies could thus offer an inflection point for food systems transformation.

As elaborated above, looming threats to farming flagged in the academic and policy literatures include high input costs, climate change, and land degradation. These factors can cause poverty in farming communities or even jeopardise the economic viability of farming. Five key farmer priorities were extrapolated from these threats to farming, namely, raising core productivity, coping with abiotic stresses (heat stress, water stress, salinity), coping with biotic stresses (pests, diseases), lowering input costs, and improving product quality. These priorities mirror those highlighted by myriad farmers in their discussions with the authors over the years, both in Malta and in African countries.

Pertinent academic papers were then identified and reviewed, including both in vivo and in vitro studies on the efficacy of microalgae-based inputs vis-à-vis agricultural crops. This involved entering combinations of search terms into Google Scholar, notably 'microalgae', 'spirulina', or 'chlorella' in conjunction with 'crop' or 'agriculture'.

For each combination of terms, the first 50 hits were examined. Further, any relevant studies mentioned in these papers were likewise examined. All identified studies that included *Arthrospira* and/or *Chlorella* treatments were selected, as were all studies focused on tomato, given its prominence as a global crop and target for studies on microalgae-based crop inputs. Some particularly pertinent studies involving other microalgae and crops were also included to bolster the evidence presented, specifically to ensure sufficient evidence on each distinct crop support function observed. Every study on other microalgae included in this review was selected to be broadly representative of the existing evidence for that species, vis-à-vis the types of crop support provided, in cases where multiple studies were identified.

A supplementary search was also conducted to obtain further evidence on one observed crop support function, namely, the scope for microalgae to help control crop pests and diseases. This search was performed because the original search had found limited evidence on this theme. This search used the terms 'microalgae', 'spirulina', or 'chlorella' in conjunction with 'fungus', 'nematode', or 'virus'. The studies whose findings were reported were selected to cover these different biotic stresses in ways that were broadly representative of the available evidence on each threat.

The main reasons for focusing on *Arthrospira* and *Chlorella* are their greater accessibility and stronger evidence base. Another reason, however, is to keep the present review manageable, since it is already complex, given its scope spanning different farmer priorities. Other steps taken to ensure the review remains manageable were to focus primarily on tomatoes and on just three categories of biotic pathogens.

The headline findings of the studies reviewed were summarised, specifically the observed effects of microalgae-based treatments on crops. The review could be said to take a "farmers' eye perspective" on this literature, since it seeks to make this highly technical literature more accessible to potential users, like farmers and policymakers. Critically, the evidence reported in the Results Section is organised based on its relevance to key farmer priorities. The review also aims to convey headline findings in plain language and then set them in the context of unfolding food system dynamics. The Discussion Section then covers the significance of these technologies, how their promise is not yet widely recognised, policy linkages, and research priorities.

The evidence reported in the studies reviewed fell into distinct categories based on the different types of crop support observed. Of the five farmer priorities flagged above, the reported effects of microalgae-based treatments on crops were relevant to four, namely, raising core productivity, coping with biotic stresses, coping with abiotic stresses, and improving product quality. It was not possible to assess their relevance to the fifth farmer priority ('lowering farm costs'), since no evidence on costs or economic benefits was reported by the studies reviewed.

Despite only having evidence relevant to four farmer priorities, the review findings were grouped into five efficacy pathways. This step was taken because two discrete ways for microalgal inputs to boost core productivity were observed, namely, via biofertilisation and biostimulant effects. Each efficacy pathway represents one way in which microalgal treatments showed efficacy vis-à-vis agricultural crops. Each pathway could be said to constitute a distinct agricultural technology, since each offers a technological pathway for supporting crop production. Figure 2 illustrates the efficacy pathways, while Table 1 presents the resulting evidence framework.

Despite its potential to support cropping by serving as a soil amendment, biochar produced from microalgal biomass is not covered in the present review. While this microalgal application may hold promise [43], such studies were not identified by the literature search conducted, perhaps because they may focus on the carbon sequestration benefits of biochar rather than its potential for crop support [44,45].

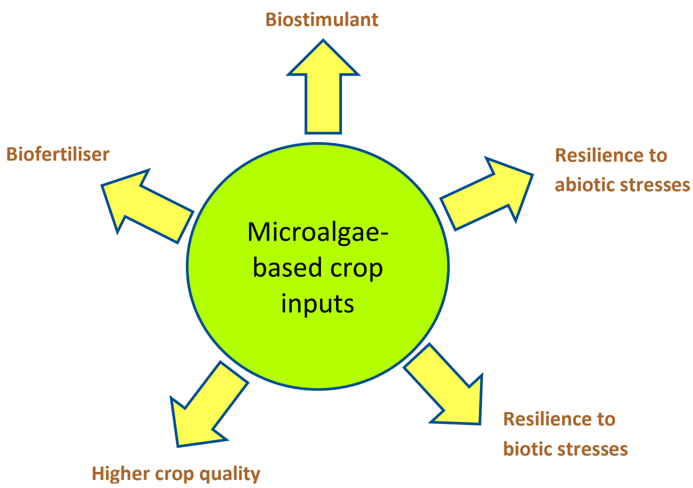

Figure 2. Distinct efficacy pathways of microalgae-based crop inputs.

Table 1. Evidence framework for the five target efficacy pathways of microalgae-based crop inputs.

#	Efficacy Pathway	Farmer Priority	Description
1	Biofertiliser	Raise core productivity	Needed nutrients are provided to crops
2	Biostimulant	Raise core productivity	Plant metabolism or functionality is stimulated
3	Resilience to abiotic stresses	Cope with abiotic stresses	Resilience of crops to threats like heat stress, water stress, or salinity is enhanced
4	Resilience to biotic stresses	Cope with biotic stresses	Resilience of crops to threats from pests and diseases is enhanced
5	Higher crop quality	Improve product quality	Crop quality parameters like soluble sugars, shelf life, or size are improved, while scope is created for organic certification

Each efficacy pathway is described, then evidence is presented. All effects are expressed in terms of the observed percentage change in parameters with treatments relative to untreated controls while defining each control. Wherever possible, comparisons of effects achieved with microalgal treatments versus conventional inputs are also provided.

3. Results

The following tables and accompanying text briefly summarise the evidence reported in the studies reviewed. These results are presented using the evidence framework provided in Table 1, namely, in terms of five target efficacy pathways of microalgae-based crop inputs.

3.1. Efficacy Pathway 1: Biofertilisation

Microalgae-based inputs can serve as biofertilisers, or natural ways to provide crops with needed macro- and micronutrients. Fertilisation is a way to boost plant growth and thus crop productivity.

Fertilisation effects are demonstrated by comparing microalgal treatments with unfertilised controls and/or the use of proven fertilisers like chemical products or manure.

Measures used by the studies reviewed to assess fertilisation effects include plant growth parameters, like height, leaf number, and flower number; changes in the content of key compounds in plant tissues, like chlorophyll or carotenoids; and yield changes, like more or larger crops. While growth parameters and key compounds in plant tissues may not be directly linked to crop yields, they could clearly positively impact them, even if these linkages have not yet been fully explored. These effects are summarised in Table 2.

Table 2. Biofertiliser effects of microalgae-based inputs.

Crop(s)	Treatment	Details	Key Findings vs. Control		
Tomato Suchithra et al., 2022 [46]	Tested *Chlorella* as a biofertiliser, then compared this to an unfertilised control	Applied dried biomass via both spraying and soil drench in a laboratory.	# of branches		+122%
			# of leaves		+75%
			Root length		+47%
			Fruits/plant		+113%
			Yield/plant		+99%
Tomato Supraja et al., 2020 [47]	Tested a microalgal mix as a biofertiliser on highly degraded soils, then compared this to unfertilised controls	Applied extracts of *Chlorella*, *Scenedesmus*, *Spirulina*, and *Synechocystis* via seed pretreatment and foliar spraying in a lab		Seed treatment	Spraying
			Shoot length	+344%	+45%
			Root length	+341%	+111%
			Plant dry weight	+372%	+86%

Table 2. *Cont.*

Crop(s)	Treatment	Details	Key Findings vs. Control			
Tomato Garcia-Gonzalez and Sommerfeld 2016 [48]	Tested extracts and dried biomass of *Acutodesmus dimorphus* as a biofertiliser on tomatoes, then compared this to unfertilised controls	Applied both extracts and dried biomass as seed pretreatment, soil amendment, or foliar spray in a greenhouse		Soil amendment	Spraying	
			Plant fresh wt	+940%	+433%	
			# of branches	+113%	+82%	
			# of flowers	+68%	+234%	
			# of fruits	+400%	n.a.	
Tomato, pepper Elarroussi et al., 2016 [49]	Tested *Arthrospira platensis* on both tomatoes and peppers, then compared this to controls using distilled water	Applied extracts via foliar spraying in a greenhouse		Tomatoes	Peppers	
			Plant height	+31%	+24%	
			# of leaves	+50%	+33%	
			Leaf area	+100%	+57%	
			Root dry wt	+230%	+67%	
			Root nodes	+100%	+50%	
Aubergine Dias et al., 2017 [50]	Tested *Arthrospira* as a biofertiliser at three different concentrations, then compared this to unfertilised controls	Applied a commercial product based on *Arthrospira* (Spirufert) via foliar spraying under both laboratory and field conditions	Doses:	Low	Med	High
			Plant height	+8%	+16%	+12%
			Stem diameter	+22%	+2%	+32%
			# of leaves	+59%	+77%	+110%
			# of flowers	+1%	+46%	−49%
			Yield/plant	+75%	+59%	−21%
Strawberries Kim et al., 2022 [51]	Tested *Chlorella* as a biofertiliser, then compared this to untreated controls	Applied microalgae culture solution via irrigation water	Fresh weight	+48%		
			Fruit yield (g)	+18%		
			Chlorophyll	+55%		
			Sugar content	+21%		
Tomato Jimenez et al., 2020 [52]	Tested *Monoraphidium* as a biofertiliser, then compared this to a chemical fertiliser and no fertiliser	Applied dried biomass to plants in a growth chamber		Microalgae	Chemical	
			Plant dry wt	+32%	+27%	
			# of leaves	+32%	+45%	
Strawberry El-Shall 2012 [53]	Tested options to partly replace chemical fertiliser with biofertiliser, including compost and *Arthrospira*	Applied live microalgae culture via irrigation on a private farm	A combination of 50% chemical fertiliser and 50% mix of compost and *Arthrospira* gave the best results. This included plant height (+28%), fruit yield (+32%), total sugars (+23%), and vitamin C (+15%).			

Headline observations include the following:

- Microalgae-based biofertilisers can offer comparable efficacy to chemical fertilisers;
- These biofertilisers can have dramatic impacts on crops in some cases, which may be linked to addressing major crop stresses such as badly degraded land, as with [46,47];
- The findings reported in Table 2 are categorised as biofertiliser effects but may also include biostimulant effects, though only some authors noted this fact.

Microalgae is a slow-release fertiliser. Unlike chemical fertilisers, its nitrogen is in organic form and must be mineralised before it can be used by plants. One study found that only 3% of algal nitrogen was immediately available to plants, rising to 33% within 21 days [54]. Being slow-release has downsides but also benefits. Notably, another study reported that nitrogen from microalgae is much less likely to leach into local waterways than nitrogen from chemical fertilisers [52].

3.2. Efficacy Pathway 2: Biostimulation

Microalgae-based inputs can also serve as biostimulants. These are defined as natural substances, mixtures thereof, or microorganisms that stimulate plants' metabolism or functionality, for instance, by improving their nutrient-use efficiency [55]. Biostimulants complement fertilisers, since they can optimise fertiliser use and thus further boost crop productivity and/or reduce nutrient application rates [56]. Biostimulation effects offer another way in which microalgae-based inputs can boost crop growth and yields, alongside biofertilisation effects.

Biostimulant effects on crops are demonstrated by comparing the efficacy of using a fertiliser on its own to that of using a fertiliser coupled with a microalgae-based biostimulant.

Measures used by the studies reviewed to assess biostimulant effects mirror those used to assess biofertilisation effects. These include observed changes in growth parameters, key compounds in plant tissues, and crop yields. These effects are summarised in Table 3.

Table 3. Biostimulant effects of microalgae-based inputs.

Crop(s)	Treatment	Details	Key Findings vs. Control			
Tomato Oancea et al., 2013 [57]	Tested *Nannochloris* + fertiliser, then compared this to a fertilised control	Applied extract via foliar spraying in a greenhouse	Root length	+8%		
			# of leaves	+20%		
			# of fruits	+19%		
Tomato Mutale-Joan et al., 2020 [37]	Tested *Arthrospira* and *Chlorella* (among others) + fertiliser, then compared them to a fertilised control	Applied microalgae extracts via soil drench in a laboratory		*Arthrospira*	*Chlorella*	
			Root length	+69%	+38%	
			Root dry wt	+6%	+5%	
			Shoot dry wt	+44%	+34%	
Tomato Suchithra et al., 2022 [46]	Tested *Chlorella* + cow dung (natural fertiliser), then compared this to a control with cow dung only	Applied dried *Chlorella* via both foliar spraying and soil drench in a lab	# of branches	+35%		
			# of leaves	+39%		
			Root length	+13%		
			Fruits/plant	+46%		
			Yield/plant	+55%		
Tomato Rachidi et al., 2020 [38]	Tested *Arthrospira platensis*, *Dunaliella salina*, and *Porphorydium spp*, then compared to a fertilised control	Incorporated microalgae extracts into irrigation in a greenhouse		Ap	Ds	P spp
			# of root nodes	+75%	+75%	+75
			Root dry wt	+12%	−3%	−3%
			Shoot dry wt	+8%	+47%	+44%
Tomato, rice Van Do et al., 2020 [58]	Tested pretreatment of seeds with *Chlorella*, then compared this to no seed pretreatment	Applied extract to plants via seed pretreatment		Tomato	Rice	
			Days to first germination	2 days	3 days	
			Days to 95% germination	1 day	3 days	
Spinach, chives Kim et al., 2018 [59]	Tested *Chlorella* as a biostimulant, then compared this to a control fertilised with compost	Applied microalgae culture via both foliar spraying and irrigation in greenhouses		Spinach	Chives	
			Yields	+18%	+32%	
Strawberry Chaouch et al., 2023 [60]	Tested a mixture of microalgae species including *Arthrospira* and *Chlorella* as a biostimulant, then compared this to an untreated control	Applied microalgae via a commercial product at two different concentrations		Low dose	High dose	
			# of roots	+31%	+65%	
			Root length	+370%	+270%	
			# of leaves	+27%	+21%	
			# of stems	+170%	+100%	
			Shoot height	+5%	+11%	

Headline observations include the following:

- Microalgal biostimulants can powerfully boost crop growth over and above any role of microalgae in fertilisation;

- Faster maturation and higher crop yields are among the potential benefits of these biostimulants;
- Some of the most dramatic impacts on crops involve hidden effects, like increased root growth and changes in plant chemistry, yet such changes could help ensure plant survival in the face of stresses.

3.3. Efficacy Pathway 3: Abiotic Resilience

Climate change poses a grave risk to crop production. Notably, it can cause abiotic stresses like heat stress, water stress, and high salinity, which can undermine crop production or even cause crop failure [11]. Land degradation can likewise cause abiotic stresses by reducing the fertility and water-holding capacity of soils [19]. Microalgae-based inputs can help crops cope with such stresses by boosting the resilience of these plants, including both helping them survive and limiting any reductions in yield. The net effect is to lessen harm to crops from these stresses. Identifying the mechanisms at play lies beyond the scope of this review, but it is notable that treated crops often have longer roots, which could help them cope with abiotic stresses via better access to water and nutrients.

Abiotic resilience effects are demonstrated by comparing plant growth or yields under abiotic stress conditions with and without microalgae treatment. The resilience effects observed with microalgal treatments could, in theory, have been compared with established means of coping with these abiotic stresses, but such comparisons were not made by the studies reviewed. For instance, they might have been compared with using seed varieties tailored to cope with water stress [61], heat stress [62], or elevated salinity [63]. Another established strategy for coping with such threats is switching to crops that better tolerate them [64], but comparing production from different crops would not fit with the present analysis. Alternatively, different types of innovative NbS-based inputs could have been assessed to compare their capacity to help crops cope with abiotic stresses [65,66], but this, too, fell outside the scope of this analysis.

It should be noted that some other analyses highlight different impacts of microalgae-based crop inputs without framing them as distinct efficacy pathways, such as microalgal ‘biofertilisers’ having effects on both core productivity and coping with abiotic stresses [56]. By contrast, the present analysis separates out such effects and calls them distinct efficacy pathways due to the potential importance of these different effects to farmers. For instance, abiotic stresses could gravely threaten cropping, so resilience to them could have profound implications for farmers.

Measures used by the studies reviewed to assess abiotic stress effects mirror those used in the previous two sections, with the only difference being that assessments were performed in the presence of abiotic stresses. These measures include observed changes in growth parameters, key compounds in plant tissues, and crop yields. These effects are summarised in Table 4.

Table 4. Enhancing resilience to abiotic stresses.

Crop(s)	Treatment	Stress faced	Details	Key Findings vs. Control			
Tomato Oancea et al., 2013 [57]	Tested *Nannochloris* + fertiliser, then compared this to a fertilised control	Water stress	Foliar spraying extract onto plants in a greenhouse	Root length	+41%		
				# of leaves	+39%		
				# of fruits	+63%		
Maize Martini et al., 2021 [67]	Tested *Chlorella* + fertiliser, then compared this to a fertilised control	Drought, nutrient deficiency	Incorporated fresh microalgae cultures and extracts into irrigation water		Normal	Drought	Low N
				Root length	+29%	+66%	+70%
				Root volume	+25%	+22%	+19%
				# of roots	+26%	+53%	+67%

Table 4. *Cont.*

Crop(s)	Treatment	Stress faced	Details	Key Findings vs. Control		
Wheat El-Baky et al., 2010 [68]	Tested *Arthrospira* on plants partially irrigated with seawater, then compared this to untreated controls	Salinity	Incorporated extracts into irrigation water that included 10% or 20% seawater		SW (10%)	SW (20%)
				Carotenoids	+62%	+55%
				Tocopherols	+102%	+98%
				Phenolic	+126%	+93%
				Protein	+33%	+42%
Taro Feng et al., 2022 [69]	Treated taro under continuous and non-continuous cropping with *Arthrospira* and *Chlorella*, then compared to a control without microalgae	Soil degradation	Applied intact microalgae via irrigation water		*Arthrospira* + continuous	*Chlorella* + continuous
				Plant height	+13%	+23%
				Leaf length	+31%	+44%
				Protein	+56%	+33%
				Results from continuous cropping + algae treatment are similar to those from non-continuous cropping without this treatment		
Fava bean Selem 2019 [70]	Treated beans facing salt stress with *Arthrospira*, then compared to untreated controls	Salt stress	Incorporated *Arthrospira* into irrigation water of salt-stressed plants	Chlorophyll a + b	+24%	
				Carotenoids	+59%	
				Weight 100 seeds	+22%	
				Photosynthetic activity	+24%	
Strawberry Soppelsa et al., 2019 [71]	Tested a microalgae extract for its capacity to overcome nutrient stress, then compared this to a commercial biostimulant	Nutrient stress	Tested natural substances in a hydroponic growing system without fertilisation		Microalgae	Commercial
				Root biomass	+393%	+153%
				Fruit yield	0%	+17%
Cucumber, lettuce El Hafiz et al., 2015 [72]	Treated seeds facing salt stress with *Chlorella* culture, then compared this to an untreated control	Salinity, water stress	Pretreated seeds with live culture in both Petri dishes and potted soil		*Chlorella* vs. control	
				1 week no water	Survived vs. withered in 3–4 days	
				Chlorophyll in cucumber	+86%	
				Chlorophyll in lettuce	+28%	

Headline observations include the following:

- Water stress, heat stress, and high salinity pose serious threats to crop production, as does land degradation;
- Microalgae-based inputs appear to be well suited to helping crops cope with such stresses;
- Indeed, the gains from using microalgae-based inputs seem to be biggest when crops face abiotic stresses;
- Microalgae-based crop inputs sometimes outperform conventional stimulants and growth enhancers.

Some of the studies reviewed found that microalgae-based inputs were so effective at addressing abiotic stresses that the performance of treated crops facing the stress was similar to that of untreated crops not facing this stress [57,68–70]. If verified, this finding could have profound implications for farmers facing looming threats from climate change and land degradation. Simply put, these technologies could prove to be vital tools for helping farmers achieve sustainable agriculture despite such threats.

While many studies used microalgal extracts, some studies compared these extracts with intact microalgal biomass, whether dried or fresh [48,67]. Such studies typically found intact microalgae to be as effective as extracts. Given the costs and difficulty of producing extracts, this observation has potentially major implications for the prospect of scaling up the use of these technologies. If intact microalgae could be used, this might be particularly beneficial to poorer farmers, particularly if the microalgae could be produced locally.

Other studies compared the efficacy of different types of microalgae vis-à-vis cropping e.g., [37]. Such analyses suggest that *Arthrospira* and *Chlorella* are broadly competitive with the other microalgae tested and hence are viable options for study and use. Yet, they also reveal that other microalgae might offer greater efficacy in particular respects, underlining the need for work to identify and investigate promising species. For instance, *Nannochloris* showed good efficacy against saline-related stresses [52]. An example from the following section is *Dunaliella*, showing particular efficacy against tomato brown virus [73].

3.4. Efficacy Pathway 4: Biotic Resilience

Given the diversity of crop pests and diseases and how these myriad organisms can affect different crops, biotic stresses on crops are complex. Climate change can increase this complexity. In addition to causing abiotic stresses, climate change can exacerbate biotic stresses and hence threats to crop production. Specifically, it can increase exposure to pests and diseases while also heightening crop vulnerability to these stresses [11].

Many farmers seek to control crop pests and diseases using chemical pesticides or fungicides. Biopesticides—pest control products based on or derived from living organisms—offer alternatives. Their use is increasing around the world due to difficulties accessing chemical products and concerns about their health and environmental impacts [74].

Microalgae-based inputs can potentially help crops cope with biotic stresses like pests and diseases and may be considered an innovative class of biopesticides. These inputs have been observed to have efficacy against various crop pests and diseases, though this literature is in its infancy. Sometimes, they act directly on target organisms by suppressing their reproduction and/or growth, while other times, they enhance plants' capacity to resist them.

Such findings suggest that these microalgae-based inputs could be used to control the pests or diseases in question. Notably, insofar as these inputs show efficacy against biotic threats to cropping, this could create scope to substitute them for agrochemicals, at least to a point. Potential benefits of any such substitutions include safer food and scope for obtaining organic certification, as well as positive environmental impacts.

Biotic resilience effects are demonstrated by comparing performance parameters like plant growth and yields under biotic stress conditions in two distinct ways. Namely, performance with microalgal treatment was compared to (i) performance with chemical pesticides and/or (ii) untreated controls (no pest control measures). Studies comparing the efficacy of microalgal and chemical treatments show that microalgal technologies can deliver comparable outcomes to conventional pesticides, suggesting they could at least partially replace them.

Various measures were used by the studies reviewed to assess the efficacy of microalgae-based inputs for coping with different biotic stresses facing crops. The present review only reports on results that convey an intuitive sense of the potential significance of this efficacy pathway. Specifically, it focuses on direct effects on the biotic pathogens in question and the observed performance of crops facing each biotic stress. By contrast, it leaves out less intuitive aspects like underlying biological mechanisms. These effects are summarised in Table 5.

Table 5. Enhancing resilience to biotic stresses.

Crop(s)	Treatment	Stress Faced	Details	Key Findings vs. Control				
Tomato Farid et al., 2019 [75]	Tested capacity of *Chlorella vulgaris*, *C. sorokiniana*, *Chlamydomonas reinhardtii*, and *Dunaliella salina* extracts to stimulate plant defences to biotic stresses	Diverse biotic stresses	Injected extracts into plants in a laboratory, then assessed the activity of biochemical pathways related to plant defence after 48 h		Cv	Cs	Cr	Ds
				β-1,3-glucanase	+305%	+226%	+58%	+11%
				Phenylalanine ammonia lyase (PAL)	+46%	+146%	+69%	+31%
				Lipoxygenase (LOX)	+36%	+71%	+50%	+143%
Chives Kim et al., 2018 [59]	Tested *Chlorella fusca* culture on chives facing grey mould, then compared this to an untreated control	Grey mould	Applied via both foliar spraying and irrigation in greenhouses	Disease severity	−24%			
Potato Al-Nazwani et al., 2021 [76]	Tested *Chlorella* for disease inhibition and sustaining plant performance, then compared this to a chemical fungicide	Black scurf disease	Tested the efficacy of this extract given this biotic stress in a lab and a greenhouse via the agar well diffusion method		*Chlorella*	Fungicide		
				Fungal growth	−54%	−56%		
				Infected area	−88%	−95%		
				Disease severity	−42%	−58%		
				Leaf area	+49%	+39%		
				Root length	+23%	+19%		
				Total dry weight	+50%	+38%		
				Yield	+12%	+10%		
No specific crop Cosoveanu and Iacomi 2010 [77]	Tested *Arthrospira* and 3 seaweed extracts against fungi, then compared to an untreated control	Eight key fungal crop pathogens	Conducted tests using extracts via lab experiments	All extracts inhibited growth of all fungi by 90%, but *Arthrospira* did so most consistently at low concentrations (<2%)				
Sugar beet Hussien et al., 2021 [78]	Tested *Chlorella*, *Arthrospira*, and 9 other microalgae against this fungus, then compared them to a chemical fungicide	Leaf spot disease	Applied intact microalgae via foliar spraying in a lab		*Arthrospira*	*Chlorella*	Fungicide	
				Fungal growth	−100%	−70%	−100%	
				Sporulation	−100%	−100%	−100	
				Disease severity	−50%	0 data	−64%	
No specific crop Fayyad et al., 2020 [79]	Tested *Arthrospira* against different fungi, then compared to a chemical fungicide	Inhibiting key fungal pathogens	Applied the extract via the well-diffusion method in a lab		*Arthrospira*	Fungicide		
				Botrytis growth	−89%	−70%		
				Aspergillus growth	−78%	−80%		
				Botrytis sporulation	−35%	−77%		
				Aspergillus sporulation	−51%	−82%		
Moringa Imara et al., 2021 [80]	Tested *Arthrospira* on infested trees, then compared this to a chemical fungicide	Damping off, root rot, and wilt disease	Experiments were conducted in pots at a research station		*Arthrospira*	Fungicide		
				Disease incidence	−50%	−45%		
				Disease severity	−59%	−84%		
				Plant survival	+50%	+68%		
				Plant fresh weight	+137%	+54%		
				Protein in leaves	+58%	+46%		
Tomato Righini et al., 2023 [81]	Tested *Anabaena minutissima* on infested plants, then compared this to untreated controls	Root rot caused by *Rhizoctonia solani*	Seeds were pretreated in different extract concentrations	Disease inhibition	Disease incidence (−36%) Disease severity (−67%)			
				Plant growth	Dry weight (+55%) Root length (+42%)			
				Plant quality	Carotenoids (+58%) Proteins (+79%)			
				Enzyme activity for plant defence	Chitinase (+400%) Glucanase (+200%)			

Table 5. *Cont.*

Crop(s)	Treatment	Stress Faced	Details	Key Findings vs. Control			
No specific crop Zielinski et al., 2020 [82]	Tested *Chlorella* as a biocontrol agent for nematodes, then compared to untreated controls	Nematode *Steinernema feltiae*, which can threaten crops	Tests were conducted using extracts on nematodes in the lab	The extract was found to be effective against parasitic nematodes, causing complete mortality of *Steinernema feltiae* at concentrations of 37.5 mg/mL or above.			
Strawberry El-ghanam et al., 2015 [83]	Tested *Arthrospira* or *Chlorella* on infested plants, then compared them to a chemical fungicide	Fruit rot disease (grey mould) caused by *Botrytis cinerea*	Applied extracts via foliar spraying at a field station		*Arthrospira*	*Chlorella*	Fungicide
				Fungal growth	−50%	−58%	−100%
				Sporulation	−96%	−98%	−100%
				Disease severity	−71%	−77%	−84%
Tomato Elsharkawy et al., 2022 [73]	Tested *Arthrospira*, *Chlorella*, and *Dunaliella* on infested plants, then compared to untreated controls	Tomato mosaic virus, which can greatly reduce yields	Plants were treated with these microalgal extracts via soil drench in a growth chamber		*Arthrospira*	*Chlorella*	*Dunaliella*
				Disease severity	−32%	−56%	−63%
				Fruit weight	+147%	+375%	+400%
				Viruses in plant	−49%	−63%	−76%

Headline observations include the following:

- Pests and diseases pose serious risks to crop production and may be exacerbated by climate change;
- Microalgae-based inputs could offer alternatives to chemical pesticides with positive wider impacts on health and the environment;
- The efficacy of such biological control agents could be developed, including via harnessing selective processes;
- One critical difference between microalgae-based technologies and chemical pesticides is that the former can positively impact crops even in the absence of biotic stresses, unlike the latter.

3.5. Efficacy Pathway 5: Product Quality

Some studies on microalgae-based biostimulants highlight improved crop quality as one of the outcomes associated with using these inputs [56]. The present analysis is structured around farmer priorities, however, and improving crop quality is a distinct and important farmer priority. As such, the present analysis frames observed crop quality effects as a distinct efficacy pathway, rather than part of the biostimulant efficacy pathway. This approach fits with the reality that any clear-cut quality effects may merit explicit focus by farmers, researchers, and policymakers.

If microalgae-based inputs can improve the quality of harvested crops, this creates opportunities for farmers to provide products that are more appealing to retailers and consumers. The use of these inputs could also support any efforts to secure organic certification. For both of these reasons, these inputs could potentially boost farmer earnings.

Quality effects are demonstrated by comparing harvested crops from treated and untreated plants. The measures used by the studies reviewed to assess quality effects include soluble sugar levels, shelf life, and size. These effects are summarised in Table 6.

Table 6. Boosting crop quality.

Crop(s)	Treatment	Details	Key Findings vs. Control						
Tomato Suchithra et al., 2022 [46]	Tested using *Chlorella* relative to no fertiliser, then *Chlorella* + natural fertiliser (dung) relative to dung only	Applied dried microalgae via both spraying and soil drench in a laboratory		*Chlorella* vs. nothing	*Chlorella* vs. dung				
			Seed weight/fruit	+333%	+160%				
			Soluble sugars	+216%	+147%				
			Protein	+482%	+88%				
			Calcium	+195%	+20%				
			Days to wrinkling	+50%	+75%				
Tomato Supraja et al., 2020 [47]	Tested a microalgal consortium consisting of *Chlorella, Scenedesmus, Arthrospira*, and *Synechocystis* as a biofertiliser on highly degraded soils relative to unfertilised controls	Applied extracts via seed pretreatment and foliar spraying in a lab		Pretreatment	Spraying				
			Chlorophyll a	+59%	+48%				
			Chlorophyll b	+132%	+87%				
			Carotenoids	+139%	+160%				
			Phosphorous	+608%	+175%				
			Potassium	+5%	+21%				
Tomato Mutale-Joan et al., 2020 [37]	Tested *Arthrospira* and *Chlorella* (among other microalgae) coupled with fertiliser, then compared to untreated yet fertilised controls	Applied extracts via soil drench in a laboratory		*Arthrospira*	*Chlorella*				
			Chlorophyll a	+33%	+38%				
			Chlorophyll b	+28%	+24%				
			Carotenoids	+33%	+67%				
			N in roots	+18%	+31%				
			P in roots	+53%	+16%				
Tomato Rachidi et al., 2020 [38]	Tested *Arthrospira platensis*, *Dunaliella salina*, and *Porphorydium* spp. coupled with fertiliser, then compared these results to an untreated fertilised control	Incorporated extracts into irrigation in a greenhouse		*Ap*	*Ds*	*Ps*			
			Carotenoids	+106%	+169%	+469%			
			Chlorophyll a	+90%	+40%	+40%			
			Chlorophyll b	−11%	−1%	+18%			
			Protein	+70%	+86%	+46%			
			Enzymatic activity [1]	+215%	+30%	+75%			
Spinach Kim et al., 2018 [59]	Tested *Chlorella fusca* culture coupled with fertiliser (compost), then compared this to an untreated but fertilised control	Applied via foliar spraying and irrigation in greenhouses on a farm	Observed % changes in mineral content						
			Ca	Fe	Mg	K	P	Zn	Cu
			+122	+311	+38	+29	+35	−30	0
Strawberry, leafy vegetables Kim et al., 2014 [84]	Treated harvested crops with *Chlorella vulgaris* then compared them with untreated controls after 14 days in cold storage	Applied live microalgae culture via foliar spraying		*Chlorella*	Untreated				
			Soluble solids	+12–22%	-				
			Strawberry decay	25–35%	95–98%				
			Lettuce decay	0%	50%				
			Kale decay	0%	80%				
			Beet decay	0%	100%				
No specific crop Christ-Ribeiro et al., 2019 [85]	Tested *Arthrospira* as a food preservative against the fungus *Penicillium verrucosum*, then compared its inhibition % to calcium propionate	Examined fungal growth in a lab on days 2, 3, 5, 7, and 9	Day #	2	3	5	7	9	
			Arthrospira	23%	16%	13%	7%	20%	
			Calcium propionate	0%	0%	0%	4%	16%	

[1] Nitrate Reductase.

Headline observations include the following:

- Microalgae-based inputs can boost crop quality in various ways, for instance, via larger fruit, more soluble sugars, and longer shelf life;
- Such quality improvements could increase farmer earnings while also benefitting consumers.

4. Discussion

The available evidence suggests that microalgal technologies hold promise for supporting crop production in five distinct ways. Several caveats are needed, however.

4.1. Caveats About the Reported Results

Most importantly, the fact that microalgae-based crop inputs possess multifaceted efficacy means that observed effects may vary in fundamental ways from one study to another. Notably, different researchers may apply similar inputs (e.g., intact spirulina incorporated into irrigation water) but report different effects on crops, as seen in the results tables. Given the multifaceted technological potential of these inputs, different researchers may focus on different facets of their potential. Clearly, this could impact what each research team observes, since if a team does not look for something, they may not find it.

Another caveat is that observed outcomes vis-à-vis any given efficacy pathway vary. Notably, while studies on microalgae-based crop treatments have mostly found them to be effective, such treatments have sometimes proven ineffective. This suggests that the efficacy of these technologies depends in part on local factors, such as how they are delivered. One implication is the desirability of clarifying key success factors or obstacles, such as elucidating and refining best-practice delivery modalities.

A third caveat is that the tables provided do not contain all the findings of the studies cited, but merely headline findings to convey key takeaway messages.

4.2. Significance of This Evidence

The literature on treating agricultural crops with microalgae-based inputs reveals powerful findings that could have profound implications for farmers and the food system.

While the effects observed in the studies reviewed cannot be directly extrapolated to farming under real-world conditions, they suggest the direction and possible magnitude of likely effects if farmers applied such technologies on their farms.

From the evidence reported, it seems clear that microalgae-based inputs could support cropping in several distinct ways, given their multifaceted technological efficacy. In some ways, their performance can be broadly comparable to agrochemicals. Examples include fertilisation and the control of harmful fungi or nematodes. In such cases, microalgal inputs could perhaps substitute for agrochemicals, at least in part. In other senses, microalgae-based inputs perform better than agrochemicals given the challenges farmers now face, such as enhancing resilience to abiotic stresses and boosting crop quality.

A major difference between agrochemicals and these microalgae-based technologies is that a given microalgal input could potentially deliver several distinct target outcomes simultaneously, while agrochemicals typically deliver just one (e.g., a fungicide controls fungal pathogens). Hypothetically, a single microalgal input could thus substitute, at least in part, for not just one agrochemical but potentially two or more. If verified, any such concurrent benefits would enhance the net gains stemming from applying microalgal inputs to crops.

Critically, this family of innovative technologies shows promise for helping farmers cope with climate change and land degradation. The evidence reported suggests that treated crops are more resilient to climate-related stresses, while microalgal crop inputs may also positively impact greenhouse gas dynamics [86]. These inputs could thus be categorised as 'climate-smart agriculture' technologies [87], given their capacity to help farmers adapt to climate change while also potentially mitigating it (alongside boosting core productivity). Concurrently, other studies found that treated crops on degraded soils performed similarly to untreated crops on fertile soils, offering hope that microalgal inputs might enable continued and ample production on degraded lands.

Beyond seemingly helping farmers cope with climate change and land degradation, these microalgal technologies can also raise crop productivity in the absence of such threats. The net effect is to boost the profitability and sustainability of cropping across diverse farming scenarios. Profitability gains stem from higher productivity and crop quality, and perhaps from replacing costly agrochemicals. Sustainability gains stem from resilience to crop stresses and positive environmental impacts.

By helping farmers face challenges, these technologies could enhance the security of food supplies as part of a wider food systems transformation. They might also support the delivery of societal goals encapsulated in the SDGs [88], such as zero hunger, good health and wellbeing, and restoration of terrestrial ecosystems. While some of the authors cited suggested such linkages, these wider impacts were not investigated by the studies reviewed.

Given their relevance to fundamental problems facing farmers and wider society (Figure 3), microalgae-based crop inputs could be seen as 'technologies for our times'. They offer one set of 'how' options to meet key objectives of both farmers (e.g., productivity) and policymakers (e.g., ensuring ample, healthy food supplies). Crop support technologies based on better-researched, more commercialised microalgae like *Arthrospira* and *Chlorella* could offer 'fast lane' options from this family of technologies. Such options could potentially be deployed relatively quickly to help address pressing problems facing farming and food supplies.

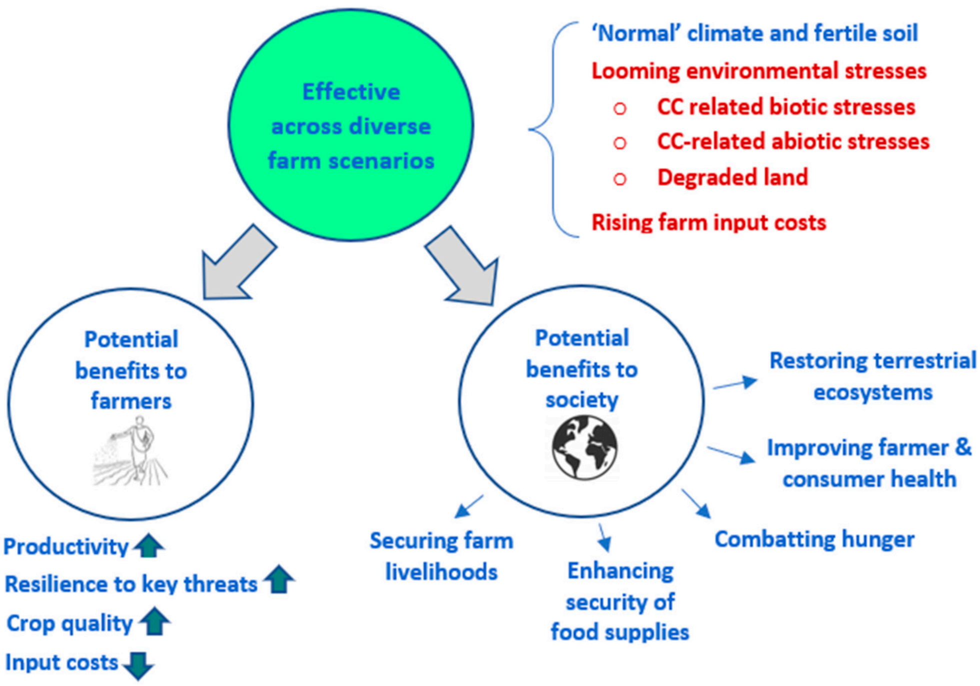

Figure 3. The potential significance of the microalgae-based crop support technologies reviewed.

The multifaceted promise of microalgal inputs spans both of the two broad categories of farmers, namely, those who rely on commercial inputs like agrochemicals and those who struggle to afford them. This latter group includes many of the 690–783 million people facing hunger and the 2.4 billion facing food insecurity, who are concentrated in Sub-Saharan Africa and South Asia [7]. For those using commercial inputs, these technologies could potentially offer safe, environmentally friendly substitutes for costly agrochemicals. For those who do not, they could address unmet input needs. If microalgae were grown locally, this could enhance their accessibility. *Arthrospira* are especially amenable to local cultivation due to growing at levels of pH, temperature, and salinity not tolerated by most other organisms, which limits biotic contamination [39,89].

A simplified way to think of these microalgal technologies is as a timely group of 'no regrets' options for farmers. 'No regrets' options are defined as those effective across a range of possible scenarios, such as different climate futures [90]. They offer ways to face situations of change, complexity, and uncertainty [91] and hence hold particular promise at present [92]. The microalgal technologies examined represent 'no regrets' options due to their ability to support farming under normal conditions and also given looming threats from climate change and land degradation. The wider benefits of these technologies for health and the environment further enhance their 'no regrets' profile.

4.3. Promise Not Yet Widely Recognised

Despite its merit and pertinence to contemporary problems, this nascent literature seems to have received relatively little attention to date. This, in turn, suggests that the promise of microalgal crop support technologies is not yet widely or fully recognised. By contrast, several other agri-food applications of microalgae seem to be better recognised, namely, their use as health foods, livestock feeds, or aquafeeds [93].

Scholarly overviews of microalgae uses all describe multiple promising applications (e.g., biofuel, bioremediation). Yet, some simply ignore crop support applications, notably those emphasising 'high value' bioproducts like nutraceuticals and cosmetics [94–97]. Others mention just one crop support application, typically biofertiliser [98–101]. A few mention two or more crop support effects, such as biofertiliser + improving crop quality [102], biofertiliser + biostimulant [103], or biofertiliser + fungicide + soil improvement [104].

Recent professional conferences about microalgae have either neglected crop support applications, e.g., [105], or only partially covered them. Just 3 of 120 papers at AlgaEurope 2023 [106] looked at microalgae for crop support. Their focus themes were (1) biofertiliser and fungicide; (2) biostimulant and fungicide; and (3) producing microalgal fungicide. Similarly, just 3 of 115 papers at the 2023 Algae Biomass Summit [107] looked at such uses. Their focus themes were (1) biofertilisers and biostimulants; (2) making fertiliser from harmful algal blooms; and (3) using live microalgae to restore degraded land and boost farm returns.

Finally, microalgal crop inputs do not appear to be widely available on farm input markets, though they may be available as components of proprietary products whose formulations are confidential. Searching the Syngenta Global website [108] for the term 'algae' gave just one hit, a biostimulant made up of multiple components [109], while 'microalgae' returned none. The Bayer Global website [110] gave 33 hits for 'microalgae' and 115 for 'algae'. Yet, none of its microalgae references mentioned crop support, and most were related to combatting algal blooms or were confidential.

Given this state of affairs, it is perhaps no surprise that high-level reports on agricultural development and the need for food systems transformation overlook microalgal crop support technologies to date, e.g., [1,17,111]. International development agencies like Oxfam [112] and CARE [113] likewise seem to overlook them, based on searches of their websites conducted for the terms 'algae' and 'microalgae'. It follows that awareness and use of these technologies are likely to be low at present among both agricultural development professionals and farmers, despite their promise and relevance to looming threats.

Various factors might contribute to the literature on microalgal crop inputs not yet attracting attention. Notably, it is in its infancy, so the evidence base is small. Many of these studies also have characteristics that could limit their impact. Some reported their findings as raw numbers with qualitative impacts (e.g., 'greater yield') instead of using intuitive metrics (e.g., percentage change vs. control). Some were written in imperfect English and published in less prominent journals. Finally, most neglected the relevance of their findings to threats from climate change and land degradation, perhaps due to the fact that this would have required interdisciplinary expertise.

Another obstacle to impact is that this literature is disjointed, given the different ways that researchers can investigate microalgal crop inputs. This could complicate the identification of trends across studies. Factors that vary include the microalgae species examined, their form (living, dried, extracts), application modality (foliar, irrigation, buried, seed pretreatment), application timing/concentration, target crops, study site (lab, greenhouse, field), local context (climate, soil type/fertility), and other inputs concurrently applied. Finally, these studies mostly focus on just one or two efficacy pathways (e.g., fertilisation, fungicide) while neglecting others.

4.4. Policy Linkages

Governments possess great power to influence farmer decisions and thus farm outcomes, notably via subsidies promoting favoured technologies. Public subsidies to agriculture are huge, totalling USD 817 billion/year worldwide based on data for just 54 countries. A recent high-level analysis of these data found that subsidies tend to favour conventional technologies and higher-income farmers while exacerbating pollution and climate change. It recommended that governments reorient agricultural policy and public support to facilitate and incentivise nature-friendly practices. Specific recommendations included developing tools to help farmers cope with climatic shocks and fostering payments for environmental services (PESs) [114]. Another high-level analysis likewise called for governments to change the rules of the game by switching subsidies from conventional to nature-friendly farming and scaling up PESs [1]. Other ways that governments could foster the greater use of NbS technologies by farmers include investing in relevant R&D, capacity building, and communications [17].

The pertinence of microalgae-based crop technologies to agriculture should ideally be recognised and harnessed by national governments and regional or international bodies via their agricultural policies and programmes. The pertinence of these technologies to other policy priorities could also be usefully explored, including their scope to help deliver aspirations vis-à-vis food security, public health, environmental management, and climate change.

Microalgae can potentially be produced using wastewater, which could lower the costs of microalgal biomass while also providing wider benefits [115]. While this practice would not be compatible with using microalgal biomass as human food or nutraceuticals, it could be suitable for crop support applications. Any such uses would, however, require that microalgal biomass complies with permitted levels of heavy metals for the jurisdiction in question [116]. The prospect of producing microalgae locally using wastewater underlines the scope for microalgae-based crop inputs to help build a circular economy.

Regulatory approval is another factor involving governments. The microalgae emphasised by the present review, *Arthrospira* and *Chlorella*, are readily available for sale across key jurisdictions like the European Union and the United States, where they have been approved as safe for consumption as food supplements. Discussions on legislation regarding the use and marketing of microalgae-based farm inputs in the EU are ongoing [56,117]. Such inputs could, however, potentially fit with the EU regulation of 2022 on fertilising products, which aims to reduce the environmental impact of fertilisers and limit risks to human health, as part of a wider set of EU policies to foster sustainable agriculture [118].

4.5. Political Economy Factors

Other powerful actors besides governments can also influence patterns of technology use by farmers.

Leading input supply companies may frame conventional technologies like agrochemicals as superior to maximise product sales. Notably, their lobbying [119] and advertising [120] could influence the thinking and decisions of policymakers and farmers regarding agricultural technologies. Where particular actors pose obstacles to harnessing innovative technologies, experience suggests that one means to neutralise their opposition is to foster pathways for them to benefit from the innovations [121]. The Food and Agricultural Organization of the United Nations (FAO) suggests that input supply firms could come to see NbS-based innovations as opportunities to embrace, given their scope to boost returns to farming while also contributing to health and environmental objectives [17]. For instance, these firms could develop NbS-based pest control measures to replace destructive chemical pesticides. Some agribusiness companies are already researching microalgae-based crop inputs [95], but this could be intensified and perhaps encouraged by government.

Similarly, key influencers might use their powerful voices and platforms to promote certain technologies over others, thus potentially skewing wider perceptions of which options hold promise. For instance, Bill Gates published an op-ed in the *New York Times* calling for greater use of agrochemicals and improved seeds in Africa while downplaying the efficacy of NbSs [122]. If such prominent individuals could instead be convinced to condone or advocate for microalgal crop support technologies, this could help harness their potential [123].

4.6. Research Priorities

Key data gaps regarding these technologies pose major barriers to harnessing their potential. These include gaps vis-à-vis basic science, options for farmers, economic impacts, barriers to adoption, and significance to wider societal goals.

The academic literature on how microalgae-based inputs can affect crops remains limited for the moment, and most existing studies involve basic research. More basic research is needed, however. This includes studies on the effects of different microalgae species or their extracts on diverse target crops, their efficacy given different crop stresses, how combining them with other inputs affects outcomes, and mechanisms underlying their efficacy. Studies are also needed on using accelerated selection [34] and genetic engineering [95] to tailor microalgae to target uses. Such research could enable progressive improvements in microalgal crop support technologies over time. Agribusinesses companies would be well suited to such work. If they embraced it, this could help ensure they see this family of innovative technologies as an opportunity, not a threat. Yet, such work could take time, given its complexity. For instance, there are estimated to be 200,000 to several million species of microalgae [36], with 175,063 species currently listed in a global database [124]. In the meantime, farmers face grave threats from land degradation and climate change, among other factors.

Given this reality, another priority is applied research on technological prospects that could offer near-term opportunities to farmers. Such work could focus on more accessible, better-researched species and the feasibility of utilising intact microalgal biomass to facilitate access and lower costs. One research need is for farm trials to assess the efficacy of these technologies in partnership with farmers under differing real-world scenarios. This includes their scope to help farmers face looming threats like climate change and land degradation. Understanding the impacts of technologies on farm profitability is key to informing farmer uptake, including any revenue gains and/or cost savings observed. Practical questions include application modalities and the scope to overcome barriers to adoption, such as knowledge gaps and resistance to change [17]. All these themes need to be examined for both farmers who rely on commercial inputs and those who struggle to access them.

A third priority is research on the scope for microalgae-based crop support technologies to help address the societal goals encapsulated in the SDGs. This includes researching their capacity to deliver the triple win promised by climate-smart agriculture, namely, higher productivity, climate adaptation, and mitigating climate change [87]. One prospect that merits particular attention is the scope for harnessing carbon market revenues to support wider uptake of these technologies or other microalgae-based agri-food technologies [86,115]. A related question concerns the capacity of these technologies to help stabilise the vulnerable farming communities in the Global South that are currently a key source of global refugee flows [125].

5. Conclusions

This review assesses the scope for microalgae-based technologies to support crop production insofar as possible, given the available evidence, then links these findings to several key societal challenges. The literature on this family of innovative agricultural technologies remains limited at present but suggests multifaceted technological promise. These technologies can foster higher crop productivity, enhanced resilience to biotic and abiotic stresses, and better-quality produce. Crucially, they seem suited to helping farmers cope with climate change and land degradation, two major threats to farming that could jeopardise food supplies. Moreover, their efficacy encompasses both farmers who rely on commercial inputs and those who struggle to afford them. In short, microalgae-based crop inputs seem to promise higher, more stable earnings for farmers across a range of economic and environmental scenarios, making them 'no regrets' options for farmers. These technologies may also offer progress towards wider food security, health, and environmental goals. Given their profile, microalgae-based crop inputs could be called 'technologies for our times'. This nascent literature remains largely neglected, however. Possible reasons for this are considered, as are prospective ways forward. The present review focuses particularly on two types of microalgae as the basis for crop inputs due to them being comparatively accessible and well-studied. Such inputs could potentially provide 'fast track' options for farmers and policymakers to address some of their key priorities and, thus, merit greater attention.

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