Tesfahun, *Cogent Food & Agriculture* (2018), 4: 1512837
https://doi.org/10.1080/23311932.2018.1512837

cogent food & agriculture

FOOD SCIENCE & TECHNOLOGY | REVIEW ARTICLE

Climate change mitigation and adaptation through biotechnology approaches: A review

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Received: 13 June 2018
Accepted: 10 August 2018
First Published: 17 August 2018

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Reviewing editor:
Fatih Yildiz, Food Engineering and Biotechnology, Middle East Technical University, Turkey

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Abstract: Climate change associated factors including temperature increases, changes in rain fall pattern and occurrence of pest and diseases negatively influence agricultural production, productivity and quality. Climate change effects particularly in region suffer persistent soil and water resource scarcity significantly increases production risk. The effects of climate change on agriculture may depend not only on changing climate condition but also on the ability to adapt through changes in technology and demand for food. Biotechnology positively reduced the effects of climate change by using modern biotechnology. Modern biotechnology through the use of genetically modified stress tolerant and high yielding transgenic crops also stand to significantly counteract the negative effects of climate change. Convectional biotechnology such as bio fertiliser and energy efficient farming are among reasonable options that could solve problems of climate change. Also this article deals with the modern technology like omics, system biology and other technology are discussed to combat abiotic stress of plant. Finally, the article highlights the current challenges and future perspective of biotechnology for climate change adaptation and mitigation.

Subjects: Agriculture & Environmental Sciences; Biotechnology; Food Biotechnology

Keywords: biotechnology; climate change; Omics; system biology; mcyobiotechnology

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PUBLIC INTEREST STATEMENT

Climate change induced increase in temperature, rainfall variation and the frequency and intensity of extreme weather events are adding to pressure on the global agriculture. The changing climate is also contributing to resource problems beyond food security, such as water scarcity, pollution and soil degradation. As resource scarcity and environmental quality problems emerge, so does the urgency of addressing these challenges. Climate change mitigation is one of the best resolutions to climate change effect. It refers to human intervention to reduce the sources or decrease intensity of negative climate change effects. Most often, mitigation scenarios involve reductions in the concentrations of greenhouse gases, either by reducing their sources or by increasing their sinks. Also biotechnology approach contributed positively by mitigating the impact of climate change through greenhouse gas reduction, and the use of synthetic fertiliser, molecular marker.

1. Introduction

According to Intergovernmental Panel on Climate Change (IPCC), climate change is the mean change or variability of its properties for long period. As per report of IPCC climate change is mainly caused by both anthropogenic which include change in land use by human action and natural forces like accent of solar cycles, volcanic eruption and continental drift (Impacts, Adaptation, and Vulnerability [IPCC], 2014). Climate change is one of the chief intimidations to agriculture in the vicinity of futures. Its most apparent effects would be on temperature, precipitation, insect pest and pathogen, weeds soil and water quality. It observed that agricultural activities contribute 25% greenhouse gas emission and major source of methane (48%) and nitrous oxide (52%) from rice fields (Lakshmi, Anuradha, Boomiraj, & Kalaivani, 2015).

Greenhouse gases are elements of both natural forces and anthropogenic which avert radiation from being to reflect in the atmosphere causing warm environment. These gases, such as carbon dioxide (CO2), methane (CH4), nitrous oxide, hydrofluorocarbons (HFCs) and sulphur hexaoxide (SF6), are mainly emitted by industries and other activities. Over period of time their concentration in the atmosphere is increased by different activities and it leads to the global climate changes (Kumar, Rohini, Mahesh Kumar, & Lalchand, 2015).

Adaptation to the climate change is possible by reducing the vulnerability of natural and human systems (Impacts, Adaptation, and Vulnerability [IPCC], 2014). Climate change mitigation is another policy retort to climate change which reduces the negative impact of climate change through involvement of human actions particularly by reducing the concentration of greenhouse gasses either by decreasing the source and increasing their sink (plants). Climate change can be mitigated by reforestation and other sink to remove concentration of CO2 from the atmosphere and shifting from biomass to renewable energy (Sallema & Mtui, 2008). Crop yield and quality is decreased due to frequent and intense precipitation events, elevated temperature, drought and other type of damaging weather, hence increasing the challenge of feeding fast growing population intricate (Hatfield et al., 2011). To feed the ever increasing world's population, their must be a need to boost agricultural production.

Agricultural biotechnology involves the practical application of biological organisms, or their subcellular components in agriculture. The techniques currently in use include tissue culture, convectional breeding and molecular marker assisted breeding and genetic engineering. Biotechnology is a promising way for mitigating the negative effects of climate change through reduction of greenhouse gasses (Teasury, 2009), use of bio fuels (Lybbert & Sumner, 2010), carbon sequestration (Kleter, Harris, Stephenson, & Unsworth, 2008), less use of fertilisers (Yan et al., 2008), tolerance of a biotic (Hsieh et al., 2002) and biotic stress (Barrows, Sexton, & Zilberman, 2014). Under this context the present article emphasises the intervention of biotechnology in climate change adaptation and mitigation for sustainable yield production and food security.

2. Role of biotechnology for climate change mitigation

2.1. Reduction GHGS emission

Agricultural practises such as use of synthetic fertiliser, cultivation rice crops, over grazing and deforestation contribute to 25% of greenhouses gasses (carbon dioxide, methane and nitrous oxide) emission in the atmosphere. Biotechnology is one of the most reliable answers to mitigate climate change through use of energy efficient farming, carbon sequestration and reduced synthetic fertiliser usage (Treasury, 2009)

Planting genetically modified crops has shown significant reduction in the amount of greenhouse gases emitted. This is owing to the fact that since genetically modified crops does not need as much maintenance as regular crops; farmers are not wasting as much fuel to power their equipment, resulting in a reduction of greenhouse gases emitted (Fares, 2014). This reduction of greenhouse gases emitted is not a negligible reduction. The reduction of these greenhouse gas emissions in 2012 was equivalent to "removing 27 billion kg of carbon dioxide from the atmosphere or equal to removing 11.9 million cars from the road for one year" (Batra, 2014). The simple yet effective implementation of genetically modified crops in farming leads farmers to expend less fuel as a result of not demanding to ride on farm equipment as long, leading to a reduction of the carbon footprint that is left behind.

2.2. Use of energy efficient farming

Now a days green biotechnology (the creation of more fertile and resistant plant resources by using specialised techniques) has been used in eradicating world hunger by using different technologies which enable the production of more fertile and resistant plants towards both biotic and abiotic stress. This technology allow farmers to use less and environmental friendly energy and fertiliser, and practise soil carbon sequestration. Production of bio fuels, both from traditional and Genetically Modified Organism (GMO) crops such as oilseed, sugarcane, rape seed and jatropha will help reduce the adverse effects of pollution by the transport sector (Sarin, Sharma, Sinharay, & Malhotra, 2007; Treasury, 2009). Efficient farming will, therefore, help in cleaning the atmosphere through plantation of perennial non edible oil-seed. Thus, directly get involved in production of bio diesel for direct use in energy sector. Then it blends along with fossil fuels, which helps to reduce the emission of carbon dioxide (Jain & Sharma, 2010: Lua et al., 2009).

2.3. Carbon sequestration

Carbon sequestration is the uptake of carbon containing substances particularly carbon dioxide from the atmosphere. It helps to collect CO_2 from the atmosphere and increase the soil organic carbon content with implication of that increased soil carbon storage mitigates climate change (Powlson, Whitmore, & Goulding, 2011). From this point of view carbon sequestration is one of the best way to mitigate climate change impact by sequestering the ever increasing concentration of CO_2 from the atmosphere. One way of increasing carbon sequestering is by conservation tillage, any tillage and planting system that covers more than 30% of the soil surface with crop residue after planting to reduce erosion by water there by enhances methane consumption and sequesters soil carbon (West & Post, 2002; Johnsona et al., 2007).

According to Table 1 genetically modified crops are led to sequestration million tons of carbon dioxide from the atmosphere. One of the best examples is Roundup Ready^{TM} which is herbicide resistant of soybean that was found to sequester 63,859 million tones of CO_2 in the USA and Argentina (Brimner, Gallivan, & Stephenson, 2004; Kleter et al., 2008). The improvement of crops opens door for the farmers to use no till farming practice. In context of climate change mitigation, these techniques improve soil quality and anchor carbon in the soil (Brookes and Barfoot, 2008).

Table 1. Summary of carbon sequestration impact 1996–2008

Crop\trait\country	Permanent fuel saving (million litres)	Potential additional CO2 saving from fuel saving (million kg)	Potential additional CO2 saving from soil saving carbon sequestration (million kg)
Us: GM HT soybeans	835	2295	38,057
Argentina:GM HT soybeans	1636	4499	43,775
Others countries: GM HT soybeans	196	539	7,939
Canada: GM HT canola	347	955	11,842
Global GM IR cotton	125	344	0
Total	3139	8632	101,613

Source: Europa bio, 2009

FAO has quantified the contribution of conservation tillage to carbon sequestration. Soil carbon sequestration for the first decade of adoption of best conservation agricultural practise was seen to decreased 1.8 t CO_2 per hectare per year, with better cycling of nutrients and avoiding nutrient losses among the key benefits to farmer FAO (2008).

2.4. Reduced use of synthetic fertiliser

Uses of synthetic fertiliser in agricultural sector have led to contaminate the environment with hazardous toxic chemicals. These synthetic fertilisers contribute for the formation as well as releases of certain greenhouses gasses (N_2O) by bringing from the soil to surrounding atmosphere when they interact with common soil bacteria. Ammonium chloride, Ammonium sulphate, sodium nitrate and calcium nitrate are the examples of inorganic fertilisers that are responsible for the formation and release of greenhouse gasses (Brookes & Barfoot, 2009).

Biotechnological option bids an advantage to reduce the use of synthetic fertiliser. Nitrogen fixing characteristics of *Rhizobium* inoculants were improved by using genetic engineering (Zahran, 2001). A bright prospect of non-leguminous plants (rice and wheat) is being enabled to fix nitrogen in the soil as reported by Yan et al. (2008) and Saikia and Jain (2007). Another strategy is planting crops in the use of nitrogen more efficiently. An example of such crops is genetically modified Canola which has shown significant reduction in the amount of nitrogen fertiliser that lost into atmosphere and leached into soil and water ways, maximising the economies of farmers through the improved profitability (Treasury, 2009).

3. Biotechnology for crop adaptation to environmental stress

The ultimate climate change effects on agriculture is reduction crop yield due to rainfall, extreme temperature, emergence of weeds, occurrence pest and disease (Johnsona et al., 2007). One of the possible ways of adapting to such global problem is apply agricultural biotechnologies that combat the negative effects of such changes is by using genetic engineering offer new opportunities for improving stress resistance (Manavalan, Guttikonda, Tran, & Nguyen, 2009).

3.1. Adaptation to abiotic stresses

Climate change causes a lot of challenges in agricultural land water use. Of these challenges, abiotic stresses including salinity, drought, extreme temperatures and chemical toxicity have negative impact on agriculture production. Climate change creates a gigantic challenge in terms of available agricultural land and fresh water use. The agricultural sector uses about 70% of the available fresh water and this is likely to increase as temperature rises (Brookes & Barfoot, 2009). Furthermore, about 25 million acres of land is vanished each year owed to salinity caused by unsound irrigation technique (Ruane et al.). It is also estimated that increased salinity in arable land will lead to 30% land uncultivated within 25 years and this number will reach up to 50% by the year 2050 as reported by Valliyodan et al (2006).

Molecular control mechanisms for abiotic stress tolerance are based on activation and regulation of specific stress-related genes. It has been reported by Zhu (2001) that salt tolerant plants also often tolerate other stresses including chilling, freezing heat and drought. Already, a number of abiotic stress tolerant, high performance GM crop plants have been developed. These include tobacco (Hong, Lakkineni, Zhang, & Verma, 2000); *Arabinopsis thaliana* and *Brasicca napus* (Jaglo et al., 2001); Tomato (Hsieh et al., 2002); rice (Yamanouchi et al., 2002) and maize, cotton, wheat and oilseed rape (Yamaguchi & Blumwals, 2005; Brookes and Barfoot, 2006). These transgenic plants maintained higher photosynthetic capacity and elevated levels of photosynthesis-related enzymes. Recently, a gene encoding aquaporin (*NtAQP1*) was identified in tobacco (*Nicotiana tabacum*) and shown to provide protection against salinity stress in transgenic tomato (*Solanum lycopersicum*) (Hu et al., 2006). *NtAQP1* plays a key role in preventing root or shoot hydraulic failure, enhancing water use efficiency and thereby improving salt tolerance.

Recently, a large body of study showed that plant Polyamines (PAs) are involved in the achievement of tolerance to such stresses as high and low temperatures, salinity, hyper osmosis, hypoxia and atmospheric pollutants (Garcıa-Jimenez, Just, Delgado, & Robaina, 2007: Liu, Kitashiba, Wang, Ban, & Moriguchi, 2007). I hereby summarise in Table 2 few transgenic plants engineered to make PAs for boosted abiotic stress tolerance.

Plants may also be engineered to reduce the levels of poly (ADP ribose) polymerise, a key stress related enzyme, resulting in plants that are able to survive drought compared to their non-GM counterparts. Field trial results have shown a 44% increase in yield in favour of such GM crops (Brookes & Barfoot, 2009). With the availability of whole genome sequences of plants, physical maps, genetics and functional genomics tools, integrated approaches using molecular breeding and genetic engineering offer new opportunities for improving stress resistance (Manavalan et al., 2009).

Recent technology developments allow studies of such stress responses at a global molecular scale using omics data (metabolome, proteome and transcriptome). The following studies are discussed to highlight good examples of System biology and omics approaches that have been used to identify key genes regulating stress tolerance and then followed with proof of those responses and phenotypes in multiple experiments including field conditions.

One of the example is a *SNAC1* (NAC transcription factor that induces the expression of a stress-tolerance genes and improves the drought and salt tolerance of rice in the field) gene which was identified from microarray experiments of stress treatments on rice (Hu et al., 2006). The transgenic plants exhibited increased sensitivity to ABA and reduced water loss.

An exhaustive screen of greater than 1,500 transcription factors in *Arabidopsis* identified nearly 40 transcription factors that when overexpressed, improved stress tolerance (Nelson et al., 2007). One of these transcription factors NF-YB1 was further characterised and shown to display significant drought tolerance in *Arabidopsis*. Microarray data of this overexpressing line showed few differences in gene expression and the genes identified were not known previously to be involved in drought tolerance.

This functional genomics approach provided a new strategy for improving drought tolerance in plants. A homolog of NF-YB1 was cloned in maize (ZmNF-YB2), overexpressed and tested for drought tolerance in the greenhouse and field plots. The transgenic maize lines were more droughts tolerant having increased chlorophyll content, photosynthesis, stomatal conductance and grain yields. One line consistently had more than 50% yield improvement in drought conditions over two different years. Generally, Table 3 provided about modern biotechnology measures for climate change problems.

Oh et al. (2009) used microarrays to identify 42 AP2 transcription factors whose expressions were affected by stress. The two transcription factors are meticulously linked but have distinct differences in affecting rice phenotype. AP37 responded to drought, salinity, cold and ABA; overexpression improved stress tolerance to all three environmental conditions. AP59 responded improved stress tolerance to drought and salinity only. Both overexpressing lines showed improved photosynthetic efficiency under stress conditions.

3.2. Mycobiotechnology

Climate change is major challenge that is already affecting people and the environment by changing average global temperature that mitigates the negative effects of extreme temperature and precipitation thereby reducing the vulnerability of farmers and ecology by improving the agro ecological resistance (Lin, Perfecto, & Vandermeer, 2008). Mycobiotechnology is fungal application of biotechnology which is used mainly for solving environmental problems and restore degraded ecosystem. These technique endeavour to use fungi for restoration harmed ecology. Saikia and

Table 2. Transgenic plants engineered to synthesize Polyamines for enhanced abiotic stress tolerance

Gene	Function and gene product	Source	Transgenic plant	Enhanced tolerance	Reference s
ADC (*Arginine decarboxylase*)	ADC is responsible for the biosynthesis of diamine Put from arginine	*Avena sativa*	*Oryza sativa* L.	Salt tolerance	Roy & Wu, 2002
		Datura stramonium	*Oryza sativa* L.	Drought tolerance	Capell, Bassie, & Christou, 2004
SAMDC (Sadenosyl methionine decarboxylase)	*SAMDC* is a key enzyme involved in the biosynthesis of the PAs	Human	*Nicotiana tabacum var. xanthi*	Salinity, drought and fungal wilts (caused by *Verticillium dahliae* and *Fusarium oxysporum*) stress tolerance	Waie, 2003
		Saccharomyces cerevisiae	*Lycopersicon Esculentum*	High temperature stress	Cheng et al., 2009
MdSPDS1 (Spermidine Synthase)	SPDS converts Put into spermidine	*Malus sylvestris*	*Pyrus communis L.“Ballad”*	Salt, osmotic and heavy metal stress Tolerance	Wen et al., 2008
		Cucurbita ficifolia	*Arabidopsis thaliana* L.	Chilling, freezing, salinity, hyper osmosis, drought and paraquat stress tolerance	Kasukabe, He, Nada, Misawa, & Hara, 2004

Source: Gill and Tuteja (2010)

Table 3. Modern agricultural biotechnologies for climate change adaptation and mitigation

Measures to climate change	Biotechnology	Application	Reference
Less fuel consumption	Engineering herbicide resistance to reduce spraying	GM soy beans GM canola	Fawcett & Towery, 2003; Brimner et al., 2004; Kleter et al., 2008
	Engineering insect resistance to reduce spraying	*Bt* maize, cotton, and eggplants	May, Gillian Champion, Dewar, Qi, & Pidgeon, 2005; Bonny, 2008.
Reduced fertiliser uses	Engineering nitrogen fixation	Genetic improvement of *Rhizobium*; inducing N-fixation to non-legumes	Zahran, 2001; Kennedy & Tchan, 1992; Saikia & Jain, 2007; Yan et al., 2008
Carbon sequestration	No-till farming due to biotechnological advances Green energy Nitrogen-efficient GM crops	Herbicide resistant GM soy beans, canola GM energy crop N-efficient GM canola	(Fawcett & Towery, 2003; Kleter et al., 2008; Lybbert & Sumner, 2010; Johnsona et al., 2007
Adaptation to climate change.	Molecular marker assisted breeding for stress resistance	Drought resistant maize, wheat hybrids	Wang, Vinocur, Shoseyov, & Altman, 2001, Wang, Vinocur, & Altman, 2003
Adaptation to biotic and abiotic stress	Engineering drought salt and heat tolerance.	GM tomato, rice	Hong et al., 2000; Jaglo et al., 2001
Improved productivity per unit area of land	Increased crop yield per unit area of land	Fungal, bacterial and viral resistant GM cassava, potatoes, bananas, maize, canola	Mneney, Mantel, & Mark, 2001; Van Camp, 2005; Gomez-Barbero, Berbel, & Rodriguez-Cerezo, 2008

Source; Sallema and Mtui (2008).

Jain (2007) reported that both endo- and ectomycorrhizal symbiotic fungi together with actinomycetes have been used as inoculants for regeneration of degraded forests.

Mycobiotechnology is part of a larger trend towards using living systems to solve environmental problems and restore degraded ecosystems. Nowadays, the sciences of mycoforestry and mycorestoration are part of an emerging field of research and application for regeneration of degraded forest ecosystems (Cheung & Chang, 2009). Mycorestoration attempts to use fungi to help in restoration of ecologically injured environments. Whether the environments have been damaged from anthropogenic or natural disasters, saprophytic and mycorrhizal fungi can help to navigate the course to recovery. A number of non-legume woody plants such as casuarinas (*Casuartna* sp.) and alders (*Alnus* sp.) can fix nitrogen symbiotically with actinomycete bacteria (*Frankia* sp.), a phenomenon that is beneficial to forestry and agroforesty (Franche, Laplaze, Duhoux, & Bogusz, 1998). Both endo- and ectomycorrhizal symbiotic fungi together with actinomycetes have been used as inoculants in regeneration of degraded forests (Saikia & Jain, 2007). Consequently, both mycorrhizal fungi and actinorhizal bacteria technologies can be applied with the aim of increasing soil fertility and improving water uptake by plants (Ruane et al.). Afforestation would indirectly contribute to improved agricultural productivity and food security because forests create microclimates that improve rainfall availability. Moreover, forests act as carbon sinks thereby contributing in sequestration and greenhouse reduction effects for climate change mitigation. Consequently, forestry and agroforestry offer the potential to develop synergies between efforts to mitigate climate change and efforts to help vulnerable populations to adapt to negative consequences of climate change (Verchot et al., 2007).

4. Challenges and futures line of work

Climate change has far reaching implications for food security, health and safety, and approaches are required for adapting to new climates. Impacts of climate change are becoming evident and there is no indication that these will reverse in the foreseeable future; action must be taken now to adapt in a timely manner and prevent unpredictable and undesirable outcomes. The world population, currently at 7 billion, is predicted to increase to 8 billion by 2025 and peak at about 9 billion in 2050 (O'Neill et al., 2010). According to Ruane et al. developing countries will need to cultivate 120 million additional hectares by crops for feeding ever increasing populations. Therefore, modern agricultural science should implement to boost crop production. Efforts should be made to incorporate local and conventional biotechnologies with modern biotechnology approaches within national policies and legal frameworks in order to increase resilience of local crop varieties against changes in environmental dynamics (Stinger et al., 2009).

Though promising result was obtained from modern biotechnology, abundant applications of biotechnology have not encountered their full potential. Of many challenges the major challenges was presented below.

- Doubt about the cause of climate variation (Natural or Human made) (Anderegg, Prall, Harold, & Schneider, 2011).
- Biotic and abiotic stress threaten for food production to feed ever increasing population (Manavalan et al., 2009).
- Raises questions about public safety issues with related to environment and health including: creation of more rigorous pests and pathogens, exacerbating the effects of existing pests, harm to non-target species, disruption of biotic communities and loss of species and genetic diversity within species (Snow et al., 2005).
- Raises ethical and socio-cultural issues like loss of traditional crops and fear of the unknown future (Qaim, 2009).

- The role of Polyamines for the abiotic stress tolerance is just commencement to be understood. A lot of effort is still required to uncover in detail the molecular mechanism of protective role of Spd, Spm and Put in abiotic stress tolerance.

In order to solve the challenges presently faced in development and application of modern biotechnology, governments ought to put in place appropriate biosafety and biotechnology policies and legal frameworks before adopting such technologies (Stringer et al., 2009). Anxieties on negative effects of GMOs have to be science based and should be studied case by case in specifying in details with true evidence. Both conventional and modern biotechnology involvements are needed to elucidate the problem. Polarised thought should be based on science not from self or political interest.

5. Conclusion

To sum up access to information and expertise in developing countries, where the need to counteract climate change and increase food production is most urgent and will be a key factor in the use of biotechnology for continued production. Plant biotechnology can contribute positively towards climate change adaptation and mitigation through reduction of greenhouse gas emissions, carbon sequestration, less fuel use and energy efficient farming and reduced artificial use. This measures help to improve agricultural productivity and protecting the ecosystem from extreme weather event. Sound application of modern biotechnology will help to counteract climate related problems and thereby securing crop production for fast growing population. An approach to safe applications of modern agricultural biotechnologies will contribute to increased yield, food security and also it will also significantly contribute to climate change adaptation and mitigation initiatives.

Funding
The author received no direct funding for this research.

Competing Interests
The author declares no competing interests.

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Citation information
Cite this article as: Climate change mitigation and adaptation through biotechnology approaches: A review, Wakjira Tesfahun, *Cogent Food & Agriculture* (2018), 4: 1512837.

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