Chapter 10
Role of Engineered Microbes in Sustainable Agriculture

Blaise Manga Enuh and Pınar Aytar Çelik

Abstract For a long time, agricultural output had been solely dependent on available environmental resources, and increasing pressure on these natural resources to meet the needs of an increasing population continues to disrupt the natural systems of the planet which has led to various consequences. In the past, scientific advancements from the use of manure to breeding experiments by Mendel were used to develop methods for the improvement of agricultural production and thus saving people from mass starvation. Scientific "fixes" have nevertheless brought forth other unforeseen issues because of the introduction of new variables. Increasing concerns over the effects of these fixes on the environment, other creatures, and ultimately humans have led to the inclusion of safety considerations and the need to consider as much as possible minimal safety limits and tests on products impacted by scientific technology. As such, recently, holistic concepts such as the circular economy and sustainable agriculture are increasingly considered with approaches inline or promoting these agendas given more attention. Among the novel approaches that promote sustainability is metabolic engineering. As a field, it has evolved over the years leveraging technological improvements in genome sequencing, computational biology, and gene editing to help bring forth innovations that have contributed to mitigating the effects on nature of intensive agricultural practices while reducing global hunger. This chapter discusses the role of engineered microbes, technologies, advancements, and future perspectives in the improvement of agriculture.

Keywords Engineered microbes · Sustainable agriculture · Cell factories · Biocontrol · Metabolic engineering

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10.1 Role of Microbes in Sustainable Agriculture

Over the years, to obtain food in the form of livestock and crops, man has developed and assembled various components to form suitable agricultural systems. Agricultural practices have been modified in several ways over the years to increase output in order to meet the increasing needs of the growing population. Presently, in the face of growing populations, the corresponding global demand for crops is projected to increase by a minimum of 60% by 2050 (Arif et al. 2020). Also, considering the recently pressing need to transition to more sustainable processes in industries that will require more fiber as starting material, there is going to be a continuous increase in the demand for agricultural output and pressure on natural resources (Arif et al. 2020). These and many other growing concerns are the focus of research to provide innovative approaches aimed at solving new challenges encountered in agriculture.

Many such innovative approaches leverage the important role microbes play in nutrient conversion both in the environment and plants (Singh et al. 2019). Microbes can be artificially introduced in agricultural settings to achieve a fertile environment that will in turn improve crop productivity (Hendrickson et al. 2008). Microbes are the prime nutrient cyclers in the environment and have intimate relationships with plants. As these microbial nutrient cycling processes occur in open systems, when using microbes in agriculture, considering the diversity of the environment and socioeconomic factors is necessary. Importantly, the unintended effects of approaches based on microbial interactions on other systems also have to be properly understood. Therefore, using microbes in sustainable agriculture will relate to the minimization of input investments and maximization of output gains to meet increasing demands while protecting soil health and water quality.

10.2 Role of Metabolic Engineering

Metabolic engineering involves modifying genetic and regulatory processes in cells to optimize a desired function in the cell. Many engineered microbes have shown important roles with potential for promoting sustainable agriculture (Table 10.1). Nevertheless, the deployment of engineered microbes in open systems such as in agriculture elicits a lot of ethical concerns especially the contamination of the natural gene pool. These ethical concerns have severely limited the use of engineered microorganisms in agriculture. This has led to the development of methods to evaluate the function of genetically modified microbes before deployment. The idea is to put bacteria communities into microscopic containers and monitor their behaviours in mimicked environmental processes. These containers are often developed with 3D printing such as root exudate collectors, microfluidic-based platforms such as RootChip, Kchip, RootArray, tracking root interaction systems, PlantChip, static droplet arrays, etc. (Ke et al. 2020). To prevent the transfer of transgenic genes to other organisms and prevent their survival and propagation in other environments,

Table 10.1 Examples of engineered microbes and relevant roles in agriculture

Application	Microorganism	Research goal	Reference
Biofertilizers	*Rhizobium leguminosarum*	Enhancing nitrogen-fixing efficiency by increasing catalase activity	Orikasa et al. (2010)
	Rhizobium meliloti and *Bradyrhizobium japonicum*	Improve nitrogen fixation and competitive activity	Ronson et al. (1990)
	Azotobacter chroococcum	Production of stimulants for *Orobanche crenata* seed germination and nitrogen fixation	Khalaf et al. (1991)
	Rhizobia and *Azotobacter*	Genetically engineered for temperature, drought, and salt tolerance to improve nitrogen to promote plant growth in severe environment	El-Saidi and Ali (1993)
	Anabaena sp. PCC 7120 (A. 7120)	Photosynthetic production of ammonium	Higo et al. (2018)
Bioremediation	*R. leguminosarum* bv. *trifolii* strain R3	Legume-rhizobia symbionts for arsenic methylation in arsenic bioremediation	Zhang et al. (2017)
	Mesorhizobium huakuii subsp. *rengei* B3	Legume-rhizobia symbionts for cadmium- and copper-polluted soils	Ike et al. (2007)
	Pseudomonas putida	Degradation of organophosphates, pyrethroids, and carbamates from pesticides	Liu et al. (2006), Gong et al. (2018)
	P. putida	Increase bioadsorption capacity of heavy metals	Valls et al. (2000)
	Sphingobium sp. JQL4-5	Degradation of methyl parathion and fenpropathrin	Yuanfan et al. (2010)
	E. coli	Simultaneous degradation of organophosphorus, carbamate, and pyrethroid pesticides	Lan et al. (2006)
Biopesticides production	*P. putida* WCS358r	Improve antifungal activity in rhizospheres of wheat plants	Glandorf et al. (2001)
	Bacillus thuringiensis subspecies *kurstaki*	Novel insecticidal proteins and increased activity against fall armyworm	All et al. (1994)
	B. thuringiensis	Improving the larvicidal activity of cry genes	Ja et al. (1996)
Bioherbicide production	*Xanthomonas campestris pv. Campestris* (XCC)	Improving virulence and host range of the plant pathogen using "Bialaphos" genes	Charudattan et al. (1996)
	Sclerotinia sclerotiorum	Development of auxotrophic properties to increase efficacy against *Cirsium arvense*	Harvey et al. (1998)
Waste management	*E. coli*	Ability to co-utilize cellobiose and xylose for biofuel production	Vinuselvi and Lee (2012)

(continued)

Table 10.1 (continued)

Application	Microorganism	Research goal	Reference
	Saccharomyces cerevisiae	Production of ethanol from xylose	Hahn-Hägerdal et al. (2001)
	Clostridium cellulolyticum	Synthesis of n-butanol using cellulose as substrate	Gaida et al. (2016)
	Bacillus subtilis	Production of para-aminobenzoic acid using xylose as substrate	Averesch and Rothschild (2019)
	Saccharomyces cerevisiae and *Actinotalea fermentans*	Synthesis of methyl halides from nonfood sources	Bayer et al. (2009)
Synthesis of high-value metabolites	*E. coli*	Production of monolignols	Chen et al. (2017)
	Saccharomyces cerevisiae	Production of tropane alkaloids	Srinivasan and Smolke (2019)
	S. cerevisiae	Production of artemisinin	Paddon et al. (2013)
	E. coli	Production of the artemisinin precursor amorpha-4,11-diene	Tsuruta et al. (2009)
	S. cerevisiae	Industrial production of isoprenoid	Meadows et al. (2016)
	S. cerevisiae and *E. coli*	Production of paclitaxel precursor	Zhou et al. (2015)
	S. cerevisiae	Production of (S)-reticuline	DeLoache et al. (2015)
	E. coli	Production of opiates	Nakagawa et al. (2016)
Food systems	*Lactobacillus plantarum*	Production of sorbitol	Ladero et al. (2007)
	S. cerevisiae	Production of xylitol	Kogje and Ghosalkar (2017)

containment systems such as genetic firewalls, auxotrophies, DNA watermarks, regulation of essential genes, and expression of toxic ones have been developed (Stirling and Silver 2020; Ke et al. 2020).

Standards for levels of containment required for deployment of suitable engineered organisms and the development of new containment systems have been established (Stirling and Silver 2020), and risk assessment methods for GMM have been presented (Rycroft et al. 2019). In addition to this, programs for biosecurity and biosafety have been initiated to study the effects of genetically modified organisms across species and generations. It is expected that these safeguards and containment programs will improve safety in the deployment of

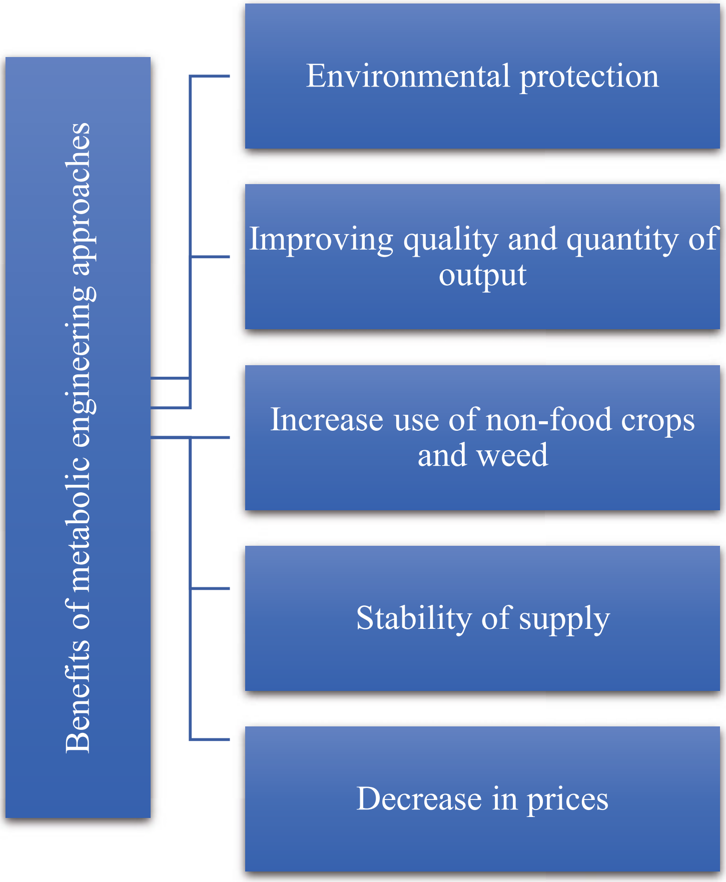

Fig. 10.1 Areas of application of metabolic engineering approaches in agriculture

genetically modified organisms into the environment. With the rapid increase in genetic engineering technologies and their applications in agriculture, there will be a need to constantly update these regulatory frameworks to keep up. This will also mean the deployment and use of safer products that in the long-run will help gain public acceptance of products impacted by genetic engineering. Several benefits are anticipated from the use of engineered microbes in agriculture (Fig. 10.1). A summary of engineered microbes and their potential applications in agriculture is included in Table 10.1.

10.3 Strategies for Metabolic Engineering Applicable in Agriculture

As previously mentioned, metabolic engineering involves the introduction of genetic changes in organisms by using recombinant DNA technology tools. Approaches used in metabolic engineering depend on the goal determined after cellular functions have been carefully analyzed (Nielsen 2001). These strategies can be used alone or in combination to achieve engineering goals in agriculture. These are as follows.

10.3.1 Heterologous Production of the Desired Metabolite

Plant metabolites such as artemisinin, flavonoids, and isoprenoids can be produced in mutant bacteria through the introduction of the synthesis pathway into bacteria. This process when successful has the advantage of avoiding challenges associated with posttranslational modifications in eukaryotic cells. Though the introduction of novel pathways could be toxic to microbes, there is a potential for the production of more diverse metabolites with more potent activity (Pfeifer and Khosla 2001; Tsuruta et al. 2009; Paddon et al. 2013; Mora-Pale et al. 2013; Trantas et al. 2015).

10.3.2 Extending the Range of Substrate to Be Used

Agricultural by-products are lignocellulosic materials containing cellulose, hemicellulose, and lignin that are the most abundant renewable organic resource on earth. Novel pathways that can break down these compounds and enable their use as substrates for the production of high-value products by efficient industrial microbial strain can be engineered in microbes. This can enable more efficient use of agricultural by-products in a renewable way (Aristidou and Penttilä 2000).

10.3.3 Introducing Pathways for the Degradation of Xenobiotics

The increasing use of xenobiotic compounds in agriculture is having negative consequences on the environment. To degrade these new synthetic compounds, completely novel pathways can be engineered in microbes to use them as substrates (McGuinness et al. 2007).

10.3.4 Improving the Physiology of the Cell or Optimizing Metabolism

Cell structural characteristics can be modified to provide more surface area for the accumulation of bioproducts, increasing the secretion of metabolite (Bu et al. 2020), reducing the consumption of precursors by competing products (Hendry et al. 2017), and optimization of flux to increase productivity (Song et al. 2017). These approaches can be used alone or in combination with other approaches to increase the production titer of high-value products and make them more competitive.

10.4 Applications of Metabolic Engineering in Agriculture

10.4.1 Increasing Yield and Resilience of Plants

Plants grow within ecosystems which often change in properties with time. For ecosystems with defined structures such as high salt concentrations in dry parts of the world, successful agriculture can be quite challenging. Microbes, however, due to their ubiquitous nature, have evolved various mechanisms to thrive in such extreme environments. For this reason, microbial genes are explored and exploited to engineer transgenic plants to impart desirable traits as tolerance to adverse conditions which in turn increases production (Gupta et al. 2013).

Another approach with biotechnology-based solutions to improve both crop yields and resilience that is gaining ground is the direct manipulation of the holobiont of plants through microbiome engineering. Microbiomes play a role in boosting plant growth, fighting against crop diseases, and mitigating abiotic stress. In addition to microbiome engineering, new practices in agriculture using this approach include microbiome breeding, transplantation, and targeted microbiome engineering, for example, by strategic soil amendments to maintain beneficial microbes or use a cocktail of microbial consortia directly on the soil as probiotic agents.

It is expected that these approaches will contribute to bring faster and more sustainable solutions to challenges in agriculture related to differences in soil type, environmental/climatic conditions, growth stage, and genotype of the plant through a more purpose-directed and effective way (Arif et al. 2020).

10.4.2 Rhizosphere Strengthening

Plant growth-promoting microbes have been shown to have various beneficial effects through the improvement of plant development by triggering the secretion of growth hormones, antioxidants, and siderophores as well as improving plant nutritional capacity. Important microbe species that produce such effects include rhizobia, *Trichoderma* sp., endophytes, and arbuscular mycorrhizal fungi (AMF). Microbes in the rhizosphere can be engineered to improve plant-microbe interactions such that plants are resilient to long-term environmental perturbations including effects that could result from climate change (Ahkami et al. 2017).

10.4.3 Increasing the Photosynthetic Efficiency of Plants

The ubiquitous nature of bacteria allows them to dwell in several extreme environments where they are endowed with efficient systems for obtaining nutrients and survival. In agriculture, cyanobacteria which like plants are autotrophic can serve as an important source of information to enhance the output of crops. Agriculture is greatly affected by location and the nature and availability of light in each area. Photosynthetic pigments capture light energy in plants but are often limited in their use of solar energy because of their specificity for particular wavelengths.

With the development of new gene editing tools, bacteriochlorophylls in cyanobacteria and purple bacteria with wider range of light capture wavelength can be engineered as chimeras with plant chlorophylls to increase their light-harvesting capacity (Swainsbury et al. 2019). Light-harvesting protein chimeras from bacteria and plant sources could help in the development of more efficient light harvesters which will translate into more energy synthesized and improved plant growth.

Other approaches benefiting from cyanobacteria metabolism can be used to modify processes along the photosynthesis pathways. For instance, the carboxysomes of cyanobacteria have been introduced into the chloroplasts of plants to improve their CO_2 fixing ability. It has been discovered that plant RuBisCO function at suboptimal levels which limits the amount of carbon fixed and hence lower nutrients acquisition in plants. These cyanobacterial carboxysomes could help improve the ability of plants to fix atmospheric carbon, improve output, and have important implications for natural resource management (Goold et al. 2018).

10.4.4 Biofertilizers

Maintaining soil health is increasingly a major requirement for the development of sustainable agricultural systems. Traditional soil enrichment approaches used chemical fertilizers to enrich the soil with particular nutrients of interest. Though highly effective, in the long term, they have been the cause of gradual degradations in soil fertility, disruption of soil microbiome, and health. More sustainable biofertilizers made from exclusively living organisms are becoming the ingredients of choice to increase soil fertility while maintaining soil health. Biofertilizers are beneficial in agriculture through the acceleration of mineral uptake, increasing crop yield, stimulating plant growth, fixing nutrients and increasing availability in soil, increasing resistance against drought, and cost-effectiveness. Microbes frequently used in biofertilizer formulations include *Rhizobium*, *Azotobacter*, *Anabaena* (nitrogen fixers), *Pseudomonas putida*, and *mycorrhizal fungi* (Giri et al. 2019; Ali et al. 2020).

Considering the safety implications of applying engineered microbes in the soil, tools to engineer beneficial soil organisms such as *Anabaena* with good stability for environmental application (Chaurasia et al. 2008) including those using recent highly scalable CRISPR-Cpf1, CRISPRi technologies that produce better and markerless mutants have been developed (Higo et al. 2018; Niu et al. 2019). With improved genetic engineering tools, more environmentally friendly mutant microbes will be engineered that will improve and encourage the use of biofertilizers.

10.4.5 Biocontrol of Other Competing Organisms

10.4.5.1 Bioinsecticides and Biofungicides

Chemical pesticides based on halogens, carbamate, and organophosphorus compounds are widely used to control pests in agricultural systems. Their use has led to secondary effects such as high toxicity to other nontargeted animals, humans, and groundwater. Biological pesticides on the other hand can be biofungicides such as those containing *Trichoderma* or bioinsecticides such as those containing *Bacillus thuringiensis*. The use of biopesticides as alternative to chemical pesticides comes with several advantages like better biodegradability, better effectiveness and selectivity, and environmental friendliness (Singh et al. 2017) which fulfill requirements for sustainability. Biopesticides are however slower to adopt due to limitations like slow kill rates, difficulties of production, costs, appropriate formulations, and previously reported poor performances (Glare et al. 2016; Bhattacharyya et al. 2016).

Various subspecies of *Bacillus thuringiensis* are used as bioinsecticides to control beetle larvae (var. *tenebrionis*), caterpillars (var. *kurstaki*, *entomocidus*, *galleriae*, and *aizawai*), and mosquito and blackfly larvae (var. *israeliensis*). Certain strains of *Bacillus subtilis*, *B. pumilus*, *Pseudomonas fluorescens*, *P. aureofaciens*, and *Streptomyces* spp. prevent plant diseases by outcompeting plant pathogens in the rhizosphere, producing antifungal compounds and promoting plant and root growth (Singh et al. 2017). Biofungicides on the other hand have been used in both the phylloplane and rhizosphere to control plant diseases caused by fungi, bacteria, or nematodes including some insect pests and weeds (Singh et al. 2017). Considering these various functions, engineering bacteria species with industrial potential could improve specificity, kill rates, strain resilience in production, and performance during application.

10.4.5.2 Bioherbicides

Bioherbicides are biological agents that are used for weed control. Weed competes with crops for nutrients; therefore it has a direct effect on the quality and quantity of the output of crops. The active components of bioherbicides are living microorganisms which are applied in high inoculum rates in a plant-specific manner for weed management. They have advantages over chemical-based herbicides such as increased selectivity and reduced risks of erosion. Despite clear expected advantages of environmental friendliness over chemical herbicides, bioherbicide production and commercialization has been limited due to several environmental (aerial, soil, or aquatic), technological (mass production and formulations), and commercial constraints (market, patent issues, production costs, and regulations) (Auld and Morin 1995; Aneja et al. 2017). Just scores of bioherbicides brands are commercially available in the world markets, and they are generally fungal-based formulations (Aneja et al. 2017).

There is very little research information on the development and use of genetically engineered microbes in bioherbicide development. This is probably in part due to many failed attempts to develop effective mutants as bioherbicides (Duke et al. 2015). However, bacteria such as the pseudomonads which have good infection ability, good quorum sensing systems, and antagonistic and phytopathogenic properties (Rekadwad and Ghosh 2018) could serve as important platforms for the development of highly efficient biocontrol agents against crop weed. Possible engineering approaches include expanding the range of plant pathogens to be targeted (Charudattan et al. 1996), improving the virulence of the biocontrol agent, and developing microbial mutants producing weed-specific phytotoxins (Zidack et al. 2001; van der Does and Rep 2007).

An additional dimension could be added to protect the environment against the development of supervirulent microbes through gene transfer by including auxotrophic characteristics into engineered strains such that the strain disappears with the elimination of the weed (Miller et al. 1989; Sands and Miller 1993; Duke et al. 2015).

10.5 Cell Factories for the Biosynthesis of High-Value Metabolites

Plants are sources of many high-value products and metabolites such as medicines, supplements, flavors, etc. This translates into a high dependence on plants in agriculture to meet the increasing demands of these products. Developing agricultural systems to grow plants for this purpose also means dependence on arable land and use of water resources. Furthermore, the long generation time for plants and their seasonality hinder the ability to constantly produce and supply plant-derived products.

With the development of genetic engineering, some of these challenges are being overcome. However, engineering plants compared to simpler organisms such as microbes encounter more issues like long generation times, scalability, and polyploidy of their genomes. Better approaches using engineered bacteria have helped overcome many more challenges encountered because of pressure on natural resources and the use of plants in general. Instead of plants, microbes engineered with plant metabolism can produce plant metabolites more sustainably (Trivedi et al. 2017).

Yeasts are well-characterized microbes with eukaryotic machinery able to produce plant metabolites upon transfer of the pathways responsible for these metabolites from plants into yeasts. This not only provides the opportunity to address the challenges of using plants but also includes the additional advantage of using plant-derived feedstock from agricultural wastes and the relatively cheaper cost of developing engineered yeast. This is possible due to improvements in sequencing technologies and better engineering tools that enable the exploration and characterization of metabolic pathways for high-value products in plants and incorporating them in small unicellular organisms (Moses et al. 2017; Goold et al. 2018).

For agricultural systems dependent on market conditions and price fluctuations, engineered microbe platforms provide an opportunity to generate a wide variety of commodities with production unaffected by seasons. This could translate to a significant contributor to sustainable economic development through cheaper production, increase in output, stable supply, and a viable market (Paddon et al. 2013; Goold et al. 2018). Improvements in technologies especially genetic engineering continue to be of consistent relevance and support to overcome challenges related to generating high-value products from plants.

New technologies using biosensors promise to provide many innovative approaches for solving persistent challenges in bioproduct synthesis (Goold et al. 2018). For more complex products, consortia of multiple microbes can be devised to reconstitute the synthesis pathway. The advantages are the possibility to construct and optimize pathways in parallel which helps reduce the time for product formation, ability to use the properties unique to each microbe, microbial synergistic effects on increasing productivity, and fewer feedback inhibition-related problems (Zhou et al. 2015). Today, though many phytochemicals can be produced from microbial cell factories using the approaches mentioned before, there are still many pathways for phytochemicals that are still to be known, including precursor supply in microbial hosts, obstruction of product transport, and low enzyme activities.

With continuous use of high-throughput technologies and exploration of more plant pathways, innovative approaches to produce new high-value phytochemicals, increase production, and lower prices will emerge (Liu et al. 2017). Enzyme mining from native and nonnative hosts, enhancement of enzyme activities, optimization, and enhancement of reaction efficiencies of multienzyme pathways in microbial hosts are approaches where new technologies can be applied to advance our understanding and improve the production of phytochemicals from microbes (Li et al. 2018).

10.6 Soil Remediation

Plant-based agriculture over the years has led to the emergence of land use concerns. The increasing need for agricultural produce will not be met through cultivating the currently available land for large-scale commercial purposes. Furthermore, contamination from industrial processes render a lot more arable land unsuitable for agriculture. Some of these effects though reversible, close to half the number of farms continue to experience nutrient depletions that are very difficult to mitigate with traditional soil amendments and chemical fertilizers (Arif et al. 2020). Other methods such as biostimulation and bioaugmentation achieve remediation efficiencies of only about 60% (Wu et al. 2016).

The increasing number of novel pollutants also makes bioremediation difficult with traditional methods; therefore fields like metabolic engineering offer the possibility to develop microbial systems with specific degradation ability for new compounds (Dangi et al. 2019). With the proper characterization of the structure and activity of microbial communities as a result of increasing molecular technologies, it is increasingly possible to predict the factors required to improve the balance in microbial communities and ecosystems (Pieper and Reineke 2000). By engineering the microbiome, the composition of soil microbes can be modified to improve ecosystems and by so doing improve the growth of plants (Foo et al. 2017). Engineering techniques that can be applied to this end include optimization of enzymes structure and substrate range (Holloway et al. 1998; Chen et al. 1999; Sharma et al. 2018). Other techniques employing microbial consortia are comparatively less developed (Brune and Bayer 2012) because they require the development of more sophisticated detection and monitoring systems (Kylilis et al. 2018).

In the future, using safe microbial chassis like *P. putida*, metabolic engineering of genetic circuits for specific degradation with the ability to resist many changing conditions will prove highly beneficial in remediating recalcitrant soils (Jaiswal and Shukla 2020).

Groundwater which is necessary for plant growth is also frequently polluted by common contaminants. For example, the frequently used 1,2,3-trichloropropane is a common contaminant that is not mineralized by any known microbe in oxic conditions. Genetically engineered microbes have nevertheless been developed that can degrade such synthetic pollutants from groundwater in combination with bioaugmentation (Janssen and Stucki 2020).

The depreciation of the quality of soils can also occur through excessive use of synthetic fertilizers or spillage of industrial wastes containing recalcitrant material. Considering the need to preserve soil health and to use remediation measures that preserve soil health in the long term, biosafety bacteria engineering could be a solution to preserve these properties. This has been demonstrated with *P. putida* strain KT2440 engineered for aerobic mineralization of 1,2,3-trichloropropane. In the study, an approach leveraging combinatorial engineering and insertion in the chromosome of the bacteria of a synthetic pathway for the degradation of 1,2,3-trichloropropane was used. The mutant bacteria were shown to utilize the compound as a sole carbon source (Gong et al. 2017). Extension of this concept to rational engineering approaches pertinent to agriculture is also being undertaken by researchers to convert microbes such as *S. cerevisiae* and *Escherichia coli* into potential bioremediation agents. These are capable of bioremediating heavy metal contamination and degrading toxic aromatic compounds (Goold et al. 2018).

10.6.1 Pesticide Bioremediation

Herbicides are used in agriculture as tools to selectively grow desired crops over other plants competing for nutrients. This means higher nutrient availability to crops and increases growth. Nevertheless, there are undesirable effects that come as a result of using herbicides in the environment. They leave behind toxic metabolites resulting from partial degradation, have effects on biogeochemical cycles due to changes in microbial communities, persistent contamination, and alterations in soil fertility that affect plant nutrition (Pileggi et al. 2020). The complexity of metabolites introduced as a result of herbicide usage usually requires sophisticated approaches such as using engineered bacteria to specifically target these new agents or use bacteria acting in synergy for complete degradation.

Bacteria and fungi have been shown to degrade herbicide compounds (Erguven 2018). Knowledge of bacteria communities such as in biofilms and their structure and function is increasingly needed to develop better systems for herbicide bioremediation. A living biofouling-resistant membrane system with a beneficial bacteria strain encoding the enzyme epoxide hydrolase which degrades epichlorohydrin commonly used for the synthesis of pesticides has been demonstrated with emerging issues such as possible horizontal gene transfer addressed through bacterial chromosomal insertion of the coding sequences. Due to the importance of the risks involved in the proliferation of engineered traits in the environment, other approaches such as the introduction of programmed death after depletion of pollutants could also minimize the risks of contamination (Garbisu and Alkorta 1999; Paul et al. 2005b).

Different methodologies for the design of safer GMMs for release into the environment have also been reviewed (Paul et al. 2005a). The strain carrying the trait in the biofilm was able to control biofilm properties through a feedback circuit and producing nitric oxide to prevent the formation of biofilms by other harmful undesirable bacteria (Wood et al. 2016).

Microbial endophytes have also been shown to contribute to herbicide tolerance in plants. With metabolic engineering approaches, the range of specific tolerance traits that can be introduced into plants using endophytic bacteria is numerous. Using different beneficial endophytic bacteria that are not toxic to a plant, biotethering could be used as an accessory method for additional resistance development in crops. These are seen as cheaper alternatives to engineering plants because the cost comes as a fraction of engineering in plants (Tétard-Jones and Edwards 2016).

More responsive systems using engineered bacteria that are responsive to stress signals from plants, engineering of endophytic bacteria with phytoremediation abilities (Barac et al. 2004) and pesticide-degrading abilities (McGuinness et al. 2007) have been reported.

10.7 Agricultural Waste Management

Waste from agricultural systems include animal waste, food processing waste, crop waste, hazardous and toxic waste.

10.7.1 Crop Waste Management

Crop wastes from agro-residues obtained after harvesting such as wheat straw, rice straw, sugarcane bagasse, rice husk often referred to as lignocellulosic substrates, and plant biomass are used by engineered microbes as substrates for high-value products like biofuels. Lignocellulosic biomass represents a cheap and the largest source of renewable carbon suitable for biotechnology production (Lin et al. 2013).

Through metabolic engineering, bacterial and yeast strains have been constructed which feature traits that are advantageous for ethanol production using lignocellulose sugars. After several rounds of modification/evaluation/modification, three main microbial platforms, *Saccharomyces cerevisiae*, *Zymomonas mobilis*, and *Escherichia coli*, have emerged, and they have performed well in pilot studies (Zaldivar et al. 2001). Thanks to genetic engineering, previous biofuel production approaches that required multiple steps in the synthesis process have been reduced to single-step processes. Also, it is now possible to use feedstock that was previously unsuitable as substrates in bioprocesses for high-value products (Majidian et al. 2018).

Biofuels are combustible organic chemicals directly or indirectly derived from biomass. Various sugars in plant biomass can be converted by microbes to biofuels (Rai et al. 2022). Currently, first-generation bioethanol derived from sugar- and starch-based feedstocks (e.g., corn, sugarcane, cereals, and sugar beets) and biodiesel derived from vegetable oil or animal fats are the most widely used biofuels. Genetically engineered microbes can be used to produce biohydrogens and biogas (Srivastava 2019). Commonly used methodologies include overexpression or deletion of enzyme systems involved in the pathway for the synthesis of the bioproduct in question and de novo biosynthesis (Lin et al. 2013). Other important chemicals such as methyl halides which are used as agricultural fumigants have also been demonstrated to be produced in high yields from engineered yeast and *Actinotalea fermentans* in a symbiotic co-culture (Bayer et al. 2009).

10.8 Food Systems

Industrial biotechnology is increasingly playing a big role in the food sector amidst increasing concerns to enhance global food security. Regulations, public perceptions of sustainability, and cultural differences are among important debates within this area. Cooperation between various stakeholders is required to harmonize these emerging concerns and pave a unanimous pathway forward (McCullum et al. 2003). Food packaging is part of the delivery processes of agricultural produce and adequate preservation is necessary using adequate biopolymers.

Polylactic acid plastic polymers are used in the production of homopolymers for mulching films and packaging material. Production systems with the yeast *Yarrowia lipolytica* were designed by expressing propionyl-CoA transferase and a variant of PHA synthase (Lajus et al. 2020). Other opportunities include the potential to improve the nutritional value of foods, for example, through the development of carotenoid-enriched functional crops and oilseed crops with boosted levels of omega 3 fatty acids. Metabolic rewiring could be used to greatly increase the accumulation of carotenoids with nutritional and health-promoting activity, as recently demonstrated in a proof-of-concept experiment (Goold et al. 2018).

Pigments produced from plants such as the water-soluble anthocyanins which are widely used in the food industry can be produced from bacteria as a substitute to laborious plant-based approaches. Engineered microbes make the production process easier through the elimination of complex extraction processes and offering a more sustainable approach (Zha and Koffas 2017).

There are growing concerns of food security related to the increasing highly processed foods with high-calorie contents but low nutritional value, food loss, and food waste. Metabolic engineering approaches have enabled microbes to produce nonnative chemicals by fermentation, such as human milk oligosaccharides (HMOs). Also, biological processes can be an alternative for current chemical processes, that have extreme conditions and costly purification steps.

Sugar alcohols have a wide range of sweetness and health-promoting benefits and they are being used in the food industry for this reason. Besides, some sugar alcohols produced from engineered strains such as xylitol (Kogje and Ghosalkar 2017) and sorbitol (Ladero et al. 2007) have potential applications as building blocks of various value-added chemicals.

10.9 Conclusions

Increasing global population and the need to ensure global food security requires the development of sustainable approaches to meet the ever-increasing needs of the population. The demands on agriculture are no longer limited to food provision but also other high-value products required to improve human lives. The transition to a circular economy as a better option toward economic and environmental sustainability requires less dependence on synthetic and chemically produced products. Agriculture provides resources for successful transition, but limitations such as increasing pressures on arable land and water resources, deforestation, seasonality, and price fluctuations negatively affect the environment and the sustainability of supply chains in bioeconomics. Increasing knowledge on plant and microbial systems thanks to recent improvements in high-throughput technologies in combination with genetic engineering presents researchers with numerous opportunities to innovate and tilt the scales once more toward sustainability. Microbial metabolic engineering is successfully addressing many challenges in agriculture though with new challenges and requirements for highly standardized regulations before implementation. The characterization of more product synthesis pathways in plants, more efficient engineering tools optimized for cell hosts, minimization of contamination of natural gene pools of other organisms, and adequate regulatory and standardization mechanisms are continuously required to improve the sustainability and acceptability of genetically engineered microbes in agriculture.

References

Ahkami AH, Allen White R, Handakumbura PP, Jansson C (2017) Rhizosphere engineering: enhancing sustainable plant ecosystem productivity. Rhizosphere 3:233–243. https://doi.org/10.1016/j.rhisph.2017.04.012

Ali R, Zulaykha KD, Sajjad N (2020) Genetically modified microbes as biofertilizers. In: Bhat RA, Hakeem KR (eds) Bioremediation and biotechnology, Techniques for noxious substances remediation, vol 4. Springer Int Publishing, Cham, pp 275–293

All JN, Stancil JD, Johnson TB, Gouger R (1994) A genetically-modified *Bacillus thuringiensis* product effective for control of the fall Armyworm (Lepidoptera: Noctuidae) on Corn. Fla Entomol 77:437–440. https://doi.org/10.2307/3495697

Aneja KR, Khan SA, Aneja A (2017) Bioherbicides: strategies, challenges and prospects. In: Satyanarayana T, Deshmukh SK, Johri BN (eds) Developments in fungal biology and applied mycology. Springer, Singapore, pp 449–470

Arif I, Batool M, Schenk PM (2020) Plant microbiome engineering: expected benefits for improved crop growth and resilience. Trends Biotechnol 38:1385–1396. https://doi.org/10.1016/j.tibtech.2020.04.015

Aristidou A, Penttilä M (2000) Metabolic engineering applications to renewable resource utilization. Curr Opin Biotechnol 11:187–198. https://doi.org/10.1016/S0958-1669(00)00085-9

Auld BA, Morin L (1995) Constraints in the development of bioherbicides. Weed Technol 9:638–652

Averesch NJH, Rothschild LJ (2019) Metabolic engineering of *Bacillus subtilis* for production of para-aminobenzoic acid—unexpected importance of carbon source is an advantage for space application. Microb Biotechnol 12:703–714. https://doi.org/10.1111/1751-7915.13403

Barac T, Taghavi S, Borremans B et al (2004) Engineered endophytic bacteria improve phytoremediation of water-soluble, volatile, organic pollutants. Nat Biotechnol 22:583–588

Bayer TS, Widmaier DM, Temme K et al (2009) Synthesis of methyl halides from biomass using engineered microbes. J Am Chem Soc 131:6508–6515. https://doi.org/10.1021/ja809461u

Bhattacharyya A, Duraisamy P, Govindarajan M, Buhroo AA, Prasad R (2016) Nano-biofungicides: emerging trend in insect pest control. In: Prasad R (ed) Advances and applications through fungal nanobiotechnology. Springer International Publishing, Switzerland, pp 307–319

Brune KD, Bayer T (2012) Engineering microbial consortia to enhance biomining and bioremediation. Front Microbiol 3:203. https://doi.org/10.3389/fmicb.2012.00203

Bu X, Lin J-Y, Cheng J et al (2020) Engineering endogenous ABC transporter with improving ATP supply and membrane flexibility enhances the secretion of β-carotene in *Saccharomyces cerevisiae*. Biotechnol Biofuels 13:168. https://doi.org/10.1186/s13068-020-01809-6

Charudattan R, Prange VJ, Devalerio JT (1996) Exploration of the use of the “Bialaphos Genes” for improving bioherbicide efficacy. Weed Technol 10:625–636

Chaurasia AK, Parasnis A, Apte SK (2008) An integrative expression vector for strain improvement and environmental applications of the nitrogen fixing cyanobacterium, *Anabaena sp.* strain PCC7120. J Microbiol Methods 73:133–141. https://doi.org/10.1016/j.mimet.2008.01.013

Chen W, Brühlmann F, Richins RD, Mulchandani A (1999) Engineering of improved microbes and enzymes for bioremediation. Curr Opin Biotechnol 10:137–141. https://doi.org/10.1016/S0958-1669(99)80023-8

Chen Z, Sun X, Li Y et al (2017) Metabolic engineering of *Escherichia coli* for microbial synthesis of monolignols. Metab Eng 39:102–109. https://doi.org/10.1016/j.ymben.2016.10.021

Dangi AK, Sharma B, Hill RT, Shukla P (2019) Bioremediation through microbes: systems biology and metabolic engineering approach. Crit Rev Biotechnol 39:79–98. https://doi.org/10.1080/07388551.2018.1500997

DeLoache WC, Russ ZN, Narcross L et al (2015) An enzyme-coupled biosensor enables (S)-reticuline production in yeast from glucose. Nat Chem Biol 11:465–471

Duke SO, Scheffler BE, Boyette CD, Dayan FE (2015) Biotechnology in weed control. In: Kirk-Othmer Encyclopedia of chemical technology. American Cancer Society, pp 1–25

El-Saidi MT, Ali AMM (1993) Growing different field crops under high salinity levels and utilization of genetically engineered Rhizobia and Azotobacter salt drought tolerant strains. In: Lieth H, Al Masoom AA (eds) Towards the rational use of high salinity tolerant plants, Agriculture and forestry under marginal soil water conditions, vol 2. Springer, Dordrecht, pp 59–65

Erguven GO (2018) Comparison of some soil fungi in bioremediation of herbicide acetochlor under agitated culture media. Bull Environ ContamToxicol 100:570–575. https://doi.org/10.1007/s00128-018-2280-1

Foo JL, Ling H, Lee YS, Chang MW (2017) Microbiome engineering: current applications and its future. Biotechnol J 12:1600099. https://doi.org/10.1002/biot.201600099

Gaida SM, Liedtke A, Jentges AHW et al (2016) Metabolic engineering of *Clostridium cellulolyticum* for the production of n-butanol from crystalline cellulose. Microb Cell Fact 15:6. https://doi.org/10.1186/s12934-015-0406-2

Garbisu C, Alkorta I (1999) Utilization of genetically engineered microorganisms (GEMs) for bioremediation. J Chem Technol Biotechnol 74:599–606. https://doi.org/10.1002/(SICI)1097-4660(199907)74:7<599::AID-JCTB82>3.0.CO;2-G

Giri B, Prasad R, Wu Q-S, Varma A (2019) Biofertilizers for sustainable agriculture and environment. Springer International Publishing. isbn:978-3-030-18932-7. https://www.springer.com/gp/book/9783030189327

Glandorf DCM, Verheggen P, Jansen T et al (2001) Effect of genetically modified *Pseudomonas putida* WCS358r on the fungal rhizosphere microflora of field-grown wheat. Appl Environ Microbiol 67:3371–3378. https://doi.org/10.1128/AEM.67.8.3371-3378.2001

Glare TR, Gwynn RL, Moran-Diez ME (2016) Development of biopesticides and future opportunities. In: Glare TR, Moran-Diez ME (eds) Microbial-based biopesticides: methods and protocols. Springer, New York, pp 211–221

Gong T, Xu X, Che Y et al (2017) Combinatorial metabolic engineering of *Pseudomonas putida* KT2440 for efficient mineralization of 1,2,3-trichloropropane. Sci Rep 7:7064. https://doi.org/10.1038/s41598-017-07435-x

Gong T, Xu X, Dang Y et al (2018) An engineered *Pseudomonas putida* can simultaneously degrade organophosphates, pyrethroids and carbamates. Sci Total Envirom 628–629:1258–1265. https://doi.org/10.1016/j.scitotenv.2018.02.143

Goold H, Wright P, Hailstones D (2018) Emerging opportunities for synthetic biology in agriculture. Genes 9:341. https://doi.org/10.3390/genes9070341

Gupta VK, Yadava LP, Donovan AO et al (2013) Microbial engineering for developing stress tolerant cultivars an innovative approach. CRC Press-Taylor & Francis Group, Boca Raton

Hahn-Hägerdal B, Wahlbom CF, Gárdonyi M et al (2001) Metabolic engineering of *Saccharomyces cerevisiae* for xylose utilization. In: Nielsen J, Eggeling L, Dynesen J et al (eds) Metabolic engineering. Springer, Berlin, pp 53–84

Harvey IC, Bourdot GW, Saville DJ, Sands DC (1998) A comparison of auxotrophic and wild strains of *Sclerotinia sclerotiorum* used as a mycoherbicide against Californian thistle (*Cirsium arvense*). Biocontrol Sci Technol 8:73–81. https://doi.org/10.1080/09583159830441

Hendrickson JR, Hanson JD, Tanaka DL, Sassenrath G (2008) Principles of integrated agricultural systems: introduction to processes and definition. Ren Agri Food Sys 23:265–271

Hendry JI, Prasannan C, Ma F et al (2017) Rerouting of carbon flux in a glycogen mutant of cyanobacteria assessed via isotopically non-stationary 13C metabolic flux analysis. Biotechnol Bioeng 114:2298–2308. https://doi.org/10.1002/bit.26350

Higo A, Isu A, Fukaya Y et al (2018) Application of CRISPR interference for metabolic engineering of the heterocyst-forming multicellular *Cyanobacterium anabaena* sp. PCC 7120. Plant Cell Physiol 59:119–127. https://doi.org/10.1093/pcp/pcx166

Holloway P, Knoke KL, Trevors JT, Lee H (1998) Alteration of the substrate range of haloalkane dehalogenase by site-directed mutagenesis. Biotechnol Bioeng 59:520–523. https://doi.org/10.1002/(SICI)1097-0290(19980820)59:4<520::AID-BIT16>3.0.CO;2-D

Ike A, Sriprang R, Ono H et al (2007) Bioremediation of cadmium contaminated soil using symbiosis between leguminous plant and recombinant rhizobia with the MTL4 and the PCS genes. Chemosphere 66:1670–1676. https://doi.org/10.1016/j.chemosphere.2006.07.058

Ja B, Kakefuda M, Gawron-Burke C (1996) Engineering *Bacillus thuringiensis* bioinsecticides with an indigenous site-specific recombination system. Appl Environ Microbiol 62:4367–4373. https://doi.org/10.1128/aem.62.12.4367-4373.1996

Jaiswal S, Shukla P (2020) Alternative strategies for microbial remediation of pollutants via synthetic biology. Front Microbiol 11:808. https://doi.org/10.3389/fmicb.2020.00808

Janssen DB, Stucki G (2020) Perspectives of genetically engineered microbes for groundwater bioremediation. Environ Sci Process Impacts 22:487–499. https://doi.org/10.1039/C9EM00601J

Ke J, Wang B, Yoshikuni Y (2020) Microbiome engineering: synthetic biology of plant-associated microbiomes in sustainable agriculture. Trends Biotechnol 39:244–261. https://doi.org/10.1016/j.tibtech.2020.07.008

Khalaf KA, Ali AM National RC (1991) Preliminary attempts to produce genetically engineered *Azotobacter chrococcum* transformants able to produce Orobanche stimulant(s) [Vicia faba]. Faba Bean Information Service

Kogje AB, Ghosalkar A (2017) Xylitol production by genetically modified industrial strain of *Saccharomyces cerevisiae* using glycerol as co-substrate. J Ind Microbiol Biotechnol 44:961–971. https://doi.org/10.1007/s10295-017-1914-3

Kylilis N, Tuza ZA, Stan G-B, Polizzi KM (2018) Tools for engineering coordinated system behaviour in synthetic microbial consortia. Nat Commun 9:2677. https://doi.org/10.1038/s41467-018-05046-2

Ladero V, Ramos A, Wiersma A et al (2007) High-level production of the low-calorie sugar sorbitol by *Lactobacillus plantarum* through metabolic engineering. Appl Environ Microbiol 73:1864–1872. https://doi.org/10.1128/AEM.02304-06

Lajus S, Dusséaux S, Verbeke J et al (2020) Engineering the yeast *Yarrowia lipolytica* for production of polylactic acid homopolymer. Front Bioeng Biotechnol 8:954. https://doi.org/10.3389/fbioe.2020.00954

Lan WS, Gu JD, Zhang JL et al (2006) Coexpression of two detoxifying pesticide-degrading enzymes in a genetically engineered bacterium. Int Biodeter Biodegr 58:70–76. https://doi.org/10.1016/j.ibiod.2006.07.008

Li S, Li Y, Smolke CD (2018) Strategies for microbial synthesis of high-value phytochemicals. Nat Chem 10:395–404. https://doi.org/10.1038/s41557-018-0013-z

Lin H, Wang Q, Shen Q et al (2013) Genetic engineering of microorganisms for biodiesel production. Bioengineered 4:292–304. https://doi.org/10.4161/bioe.23114

Liu Z, Hong Q, Xu J-H et al (2006) Construction of a genetically engineered microorganism for degrading organophosphate and carbamate pesticides. Int Biodeter Biodegr 58:65–69. https://doi.org/10.1016/j.ibiod.2006.07.009

Liu X, Ding W, Jiang H (2017) Engineering microbial cell factories for the production of plant natural products: from design principles to industrial-scale production. Microb Cell Fact 16:125. https://doi.org/10.1186/s12934-017-0732-7

Majidian P, Tabatabaei M, Zeinolabedini M et al (2018) Metabolic engineering of microorganisms for biofuel production. Renew Sust Energy Rev 82:3863–3885. https://doi.org/10.1016/j.rser.2017.10.085

McCullum C, Benbrook C, Knowles L et al (2003) Application of modern biotechnology to food and agriculture: food systems perspective. J Nutr Educ Behav 35:319–332. https://doi.org/10.1016/S1499-4046(06)60347-3

McGuinness M, Mazurkiewicz V, Brennan E, Dowling D (2007) Dechlorination of pesticides by a specific bacterial glutathione S-transferase, BphKLB400: potential for bioremediation. Eng Life Sci 7:611–615

Meadows AL, Hawkins KM, Tsegaye Y et al (2016) Rewriting yeast central carbon metabolism for industrial isoprenoid production. Nature 537:694–697. https://doi.org/10.1038/nature19769

Miller RV, Ford EJ, Zidack NJ, Sands DC (1989) A pyrimidine auxotroph of *Sclerotinia sclerotiomm* for use in biological weed control. Microbiology 135:2085–2091. https://doi.org/10.1099/00221287-135-7-2085

Mora-Pale M, Sanchez-Rodriguez SP, Linhardt RJ et al (2013) Metabolic engineering and in vitro biosynthesis of phytochemicals and non-natural analogues. Plant Sci 210:10–24. https://doi.org/10.1016/j.plantsci.2013.05.005

Moses T, Mehrshahi P, Smith AG, Goossens A (2017) Synthetic biology approaches for the production of plant metabolites in unicellular organisms. J Exp Bot 68:4057–4074. https://doi.org/10.1093/jxb/erx119

Nakagawa A, Matsumura E, Koyanagi T et al (2016) Total biosynthesis of opiates by stepwise fermentation using engineered *Escherichia coli*. Nat Commun 7:10390. https://doi.org/10.1038/ncomms10390

Nielsen J (2001) Metabolic engineering. Appl Microbiol Biotechnol 55:263–283. https://doi.org/10.1007/s002530000511

Niu T-C, Lin G-M, Xie L-R et al (2019) Expanding the potential of CRISPR-Cpf1-based genome editing technology in the *Cyanobacterium Anabaena* PCC 7120. ACS Synth Biol 8:170–180. https://doi.org/10.1021/acssynbio.8b00437

Orikasa Y, Nodasaka Y, Ohyama T et al (2010) Enhancement of the nitrogen fixation efficiency of genetically-engineered Rhizobium with high catalase activity. J Biosci Bioeng 110:397–402. https://doi.org/10.1016/j.jbiosc.2010.04.007

Paddon CJ, Westfall PJ, Pitera DJ et al (2013) High-level semi-synthetic production of the potent antimalarial artemisinin. Nature 496:528–532. https://doi.org/10.1038/nature12051

Paul D, Pandey G, Jain RK (2005a) Suicidal genetically engineered microorganisms for bioremediation: need and perspectives. BioEssays 27:563–573. https://doi.org/10.1002/bies.20220

Paul D, Pandey G, Pandey J, Jain RK (2005b) Accessing microbial diversity for bioremediation and environmental restoration. Trends Biotechnol 23:135–142. https://doi.org/10.1016/j.tibtech.2005.01.001

Pfeifer BA, Khosla C (2001) Biosynthesis of polyketides in heterologous hosts. Microbiol Mol Biol Rev 65:106–118. https://doi.org/10.1128/MMBR.65.1.106-118.2001

Pieper DH, Reineke W (2000) Engineering bacteria for bioremediation. Curr Opin Biotechnol 11: 262–270. https://doi.org/10.1016/S0958-1669(00)00094-X

Pileggi M, Pileggi SAV, Sadowsky MJ (2020) Herbicide bioremediation: from strains to bacterial communities. Heliyon 6:e05767. https://doi.org/10.1016/j.heliyon.2020.e05767

Rai AK, Makishah NHA, Wen Z, Gupta G, Pandit S, Prasad R (2022) Recent developments in lignocellulosic biofuels, a renewable source of bioenergy. Fermentation 8:161. https://doi.org/10.3390/fermentation8040161

Rekadwad B, Ghosh PK (2018) Pseudomonas: a quorum sensing system for improved crop production. In: Kalia VC (ed) Quorum sensing and its biotechnological applications. Springer, Singapore, pp 181–191

Ronson CW, Bosworth A, Genova M et al (1990) Field release of genetically-engineered *Rhizobium meliloti* and *Bradyrhizobium japonicum* strains. In: Gresshoff PM, Roth LE, Stacey G, Newton WE (eds) Nitrogen fixation: achievements and objectives. Springer, Boston, pp 397–403

Rycroft T, Hamilton K, Haas CN, Linkov I (2019) A quantitative risk assessment method for synthetic biology products in the environment. Sci Total Environ 696:133940. https://doi.org/10.1016/j.scitotenv.2019.133940

Sands DC, Miller RV (1993) Evolving strategies for biological control of weeds with plant pathogens. Pest Sci 37:399–403. https://doi.org/10.1002/ps.2780370414

Sharma B, Dangi AK, Shukla P (2018) Contemporary enzyme-based technologies for bioremediation: a review. J Environ Manag 210:10–22. https://doi.org/10.1016/j.jenvman.2017.12.075

Singh R, Kumar M, Mittal A, Mehta PK (2017) Microbial metabolites in nutrition, healthcare and agriculture. 3 Biotech 7:15. https://doi.org/10.1007/s13205-016-0586-4

Singh D, Raina TK, Kumar A, Singh J, Prasad R (2019) Plant microbiome: a reservoir of novel genes and metabolites. Plant Gene. https://doi.org/10.1016/j.plgene.2019.100177

Song T-Q, Ding M-Z, Zhai F et al (2017) Engineering *Saccharomyces cerevisiae* for geranylgeraniol overproduction by combinatorial design. Sci Rep 7:14991. https://doi.org/10.1038/s41598-017-15005-4

Srinivasan P, Smolke CD (2019) Engineering a microbial biosynthesis platform for de novo production of tropane alkaloids. Nat Commun 10:3634. https://doi.org/10.1038/s41467-019-11588-w

Srivastava RK (2019) Bio-energy production by contribution of effective and suitable microbial system. Mater Sci Energy Technol 2:308–318. https://doi.org/10.1016/j.mset.2018.12.007

Stirling F, Silver PA (2020) Controlling the implementation of transgenic microbes: are we ready for what synthetic biology has to offer? Mol Cell 78:614–623. https://doi.org/10.1016/j.molcel.2020.03.034

Swainsbury DJK, Faries KM, Niedzwiedzki DM et al (2019) Engineering of B800 bacteriochlorophyll binding site specificity in the *Rhodobacter sphaeroides* LH2 antenna. Biochim Biophys Acta Bioenergy 1860:209–223. https://doi.org/10.1016/j.bbabio.2018.11.008

Tétard-Jones C, Edwards R (2016) Potential roles for microbial endophytes in herbicide tolerance in plants. Pest Manag Sci 72:203–209. https://doi.org/10.1002/ps.4147

Trantas EA, Koffas MAG, Xu P, Ververidis F (2015) When plants produce not enough or at all: metabolic engineering of flavonoids in microbial hosts. Front Plant Sci 6:7. https://doi.org/10.3389/fpls.2015.00007

Trivedi P, Schenk PM, Wallenstein MD, Singh BK (2017) Tiny microbes, big yields: enhancing food crop production with biological solutions. Microb Biotechnol 10:999–1003. https://doi.org/10.1111/1751-7915.12804

Tsuruta H, Paddon CJ, Eng D et al (2009) High-level production of amorpha-4, 11-diene, a precursor of the antimalarial agent artemisinin, in *Escherichia coli*. PLoS One 4:e4489

Valls M, de Lorenzo V, Gonzàlez-Duarte R, Atrian S (2000) Engineering outer-membrane proteins in *Pseudomonas putida* for enhanced heavy-metal bioadsorption. J Inorg Biochem 79:219–223. https://doi.org/10.1016/S0162-0134(99)00170-1

van der Does HC, Rep M (2007) Virulence genes and the evolution of host specificity in plant-pathogenic fungi. MPMI 20:1175–1182. https://doi.org/10.1094/MPMI-20-10-1175

Vinuselvi P, Lee SK (2012) Engineered *Escherichia coli* capable of co-utilization of cellobiose and xylose. Enzyme Microb Technol 50:1–4

Wood TL, Guha R, Tang L et al (2016) Living biofouling-resistant membranes as a model for the beneficial use of engineered biofilms. PNAS 113:E2802–E2811. https://doi.org/10.1073/pnas.1521731113

Wu M, Dick WA, Li W et al (2016) Bioaugmentation and biostimulation of hydrocarbon degradation and the microbial community in a petroleum-contaminated soil. Int Biodeter Biodegr 107:158–164. https://doi.org/10.1016/j.ibiod.2015.11.019

Yuanfan H, Jin Z, Qing H et al (2010) Characterization of a fenpropathrin-degrading strain and construction of a genetically engineered microorganism for simultaneous degradation of methyl parathion and fenpropathrin. J Environ Manag 91:2295–2300. https://doi.org/10.1016/j.jenvman.2010.06.010

Zaldivar J, Nielsen J, Olsson L (2001) Fuel ethanol production from lignocellulose: a challenge for metabolic engineering and process integration. Appl Microbiol Biotechnol 56:17–34. https://doi.org/10.1007/s002530100624

Zha J, Koffas MAG (2017) Production of anthocyanins in metabolically engineered microorganisms: current status and perspectives. Synth Syst Biotechnol 2:259–266. https://doi.org/10.1016/j.synbio.2017.10.005

Zhang J, Xu Y, Cao T et al (2017) Arsenic methylation by a genetically engineered Rhizobium-legume symbiont. Plant Soil 416:259–269. https://doi.org/10.1007/s11104-017-3207-z

Zhou K, Qiao K, Edgar S, Stephanopoulos G (2015) Distributing a metabolic pathway among a microbial consortium enhances production of natural products. Nat Biotechnol 33:377–383. https://doi.org/10.1038/nbt.3095

Zidack N, Tiourabaev K, Pilgeram A, et al. (2001) Valine excreting isolate of *Pseudomonas syringae* pv. tagetis exhibits enhanced virulence against Houndstongue (*Cynoglossum officinale*). Nato science series sub series I life and behavioural sciences, vol. 339, pp 279