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New biorefineries and sustainable agriculture: Increased food, biofuels, and ecosystem security

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ABSTRACT

The sustainability revolution is the defining challenge of our time to meet increasing needs in the energy – food – water nexus without compromising the ability of next generations. To feed the world, modern agriculture is primarily based on annual grain crops that replace native perennial plant communities on most of the arable land on the planet. This practice may not be sustainable due to high inputs of fresh water, fertilizers, and herbicides; soil erosion; and runoff water pollution. Recent biotechnology breakthroughs enable the fractionation of nonfood lignocellulosic biomass to multiple components, the conversion of nonfood cellulose to starch without sugar loss, the production of in vitro meat without slaughtering livestock, and the production of healthy oil from microbes, suggesting great opportunities of new biorefineries based on nonfood biomass. Perennial plant communities have higher biomass yield per hectare, have easily resource management, store more carbon, maintain better water quality, utilize nutrients more efficiently, tolerate more extreme weather events, and resist pests better than annual crops. Sustainable agriculture based on annual grains and perennial high-biomass yield plants along with new biorefineries could produce a myriad of products from biofuels (e.g., butanol and hydrogen), biomaterials, to food/feed. Sustainable agriculture and new biorefineries could be cornerstones of the coming sustainability revolution based on the most abundant renewable bioresource – biomass.

Contents

Abbreviations: BG, beta-glucosidase; BTW, biomass-to-wheel; CBH, cellobiohydrolase; CBP, cellobiose phosphorylase; DHA, docosahexaenoic acid; Endo, endoglucanase; EPA, eicosapentaenoic acid; FCV, fuel cell vehicle; G-1-P, glucose-1-phosphate; G-6-P, glucose-6-phosphate; HEV, hybrid electric vehicle; ICE, internal combustion engine; NAD, nicotinamide adenine dinucleotide; NADP, nicotinamide adenine dinucleotide phosphate; NPP, net primary production; PEMFC, proton membrane exchange fuel cell; PGP, potato alpha-glucan phosphorylase; SFCV, sugar fuel cell vehicle

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1. Introduction

Humanity is at the beginning of its third major cultural and economic revolution – the sustainability revolution – which will be largely completed in the 21st century [1]. The agricultural revolution, beginning approximately 10,000 years ago, allowed humanity to switch from hunting and gathering to cultivating crops and domesticating animals [2,3]. The industrial revolution in the 18th century began with the efficient utilization of carbon-rich fossil fuels, which were accumulated through millions of years of deposition, and the operation of machinery in place of human and animal labor [2,3].

Similar to the previous two revolutions, the sustainability revolution will lead to transformative changes in daily lives and most aspects of societal organizations. In this revolution, the basic needs of energy and food, as well as environment are inextricably linked, and action in one area has impacts in one or both of the other areas [4]. The sustainability revolution relies heavily on renewable biomass resource that offers an avenue toward food security, a more "green" economy, and even energy independence because biomass is the most abundant renewable bio-resource, approximately five times the world's energy consumption [4]. In addition, plant biomass is more evenly distributed than fossil fuel resources so to decrease wealth transfer among energy-exporting and energy-importing countries [5].

Farming for food production is the basis of our civilization [6,7]. Henry Kissinger said "Control oil and you control nations; control food and you control the people." To feed more than seven billion people on Earth, approximately one-third of the world's arable land is under cultivation, and 70% of the world's fresh water withdrawals are used for agriculture [4,7,8]. More than three-fourths of the global cropland is sown annually for monoculture grain crops, food legumes, and oilseeds (Fig. 1A), providing calories and nutrients in the human diet, although food biomass accounts for a very small fraction (i.e., ~2%) of the annual net primary production (NPP) [4]. Further aggressive expansion of agricultural lands from forests and grasslands, where perennial plants make up most of the world's natural terrestrial biomes, is nearly impossible and will impair biodiversity and release a large amount of new CO_2 emissions [9,10]. Modern agriculture is believed to be the largest environmental destroyer to biodiversity in terms of human activities [11].

The irreplaceable role of plant biomass in meeting human needs for food, biofuels, and biobased materials raises serious questions: Is it possible to provide enough food, biofuels, and materials while minimizing the environmental footprint and conserving biodiversity in the sustainability revolution. And how? In this perspective review, we briefly review the histories of agriculture and transportation, present our out-of-the-box visions pertaining to intertwined roles between sustainable agriculture and new biorefineries based on new biotechnology breakthroughs related to synthetic food and advanced biofuels production, and highlight key R&D directions for the coming sustainability revolution.

2. Histories of agriculture and transportation

Because Winton Churchill said "The farther backward you can look, the farther forward you are likely to see," it is important to briefly review the history of agriculture and transportation as well as present their inherent problems, before out-of-the-box solutions are discussed. Because both food and transportation biofuels have to be produced from renewable biomass resource, it often raises a debate – food versus biofuels. Therefore, the sustainable agriculture whose primary goal is to produce food/feed and biomass is closely related to new roles of biorefineries that may produce a myriad of products.

2.1. Agriculture and its inherent problems

Food is basic to life and survival, to health and fitness for facing challenges, and to the proliferation of and caring for the young [2,7]. The Neolithic agricultural revolution led to one of the most profound changes in the human history, providing a more secure and bountiful way of producing food compared to hunter-gathers [2,7]. As a result, both the world population and the carrying capacity of the land have increased by three orders of magnitude [7]. Higher populations and settlement in villages, towns, and cities enabled work specialization, accelerated the rate of innovation, and increased sociopolitical organization [2].

Because human cannot digest the most abundant cellulose-rich plants, they have to eat starch-rich grain seeds. Agricultural systems began with annual crops that are grown from seeds every year and are harvested for their seeds. The high yields of annual crops are the result of long-term, intense artificial selection for increased allocation of photosynthesis to the seed and decreased intraspecific competition. To maintain monoculture crops and prevent competition from weeds, the annual tilling of the soil is essential. Tillage can be accomplished by labor-intensive hand management on small plots, by farming machinery, by annual flooding, or by controlled watering [7]. Annual cereal crops require churning of the soil, precisely timed inputs and management, and favorable weather (e.g., rainfall, temperature and sun shine) at the correct time. Thanks to shorter growing seasons, annual crops from seeds develop very small and shallow root systems, providing less protection against soil erosion, wasting water and nutrients, storing less carbon below the ground, and tolerating pests less well than native perennial plant communities [11].

The green revolution is an outcome of the extensive use of four technologies: fertilizers, improved hybrid crop plants, mechanization, and irrigation, resulting in continuous increases in the productivity of the farm land in the 20th century [7]. For example, the invention of ammonia synthesis by Fritz Haber, Nobel Chemistry Prize Laureate (1918), and its innovation (that is, the transformation of invention to product) directed by Carl Borch, Nobel Chemistry Prize Laureate (1931), enabled the availability of inexpensive synthetic nitrogen fertilizers. (Note: the ammonia synthesis from purified hydrogen and nitrogen is the most energy efficient way to fix nitrogen compared to other nitrogen-fixing techniques [7]). The key invention of Norman Borlaug, Nobel Peace Prize Laureate (1970), was the