# **Governor's Honors Program**

Agricultural Science, Biotechnology, and Research
Interview Preparation
(2024)

## Performance Task:

- Semifinalists will have **60 minutes** to complete a written performance task using information and/or data from the peer-reviewed articles listed below. *The performance task prompt will be provided on the day of the semifinalist event.*
- Your response to the performance task will be evaluated on:
  - Appropriate synthesis and use of information and/or data,
  - Overall organization and sophistication of thoughts,
  - Documentation of intext citations for sources referenced.

Semifinalists are encouraged to bring annotations (highlighting, underlining, etc.) of each of the below articles to the semifinalist event.
*Note: Any semblance of a constructed response or summaries will not be allowed in the performance task room.*

*Articles*

1. Grossman, M.R. 2019. USDA and FDA Formal Agreement on Regulation of Cultured Meat. European Food and Feed Law: 14(4):385-389
2. Karmee, S.K. 2015. Liquid biofuels from food waste: Current trends, prospect, and limitation. Renewable and Sustainable Energy Review: 53:945-953. https://doi.org/10.1016/j.rser.2015.09.041
3. Sassenrath, G.F. 2008. Technology, complexity and change in agricultural production systems. Renewable Agriculture and Food Systems: 23(4): 285-295. doi:10.1017/S174217050700213X

## Classroom Simulation:

- Semifinalists will participate in a group interview. Judges will guide discussion with general and content specific questions (e.g. performance task response).
  - The focus will be on each semifinalist's analysis, listening, and responding ability in a group environment.
- Semifinalists should be prepared to discuss their previous experiences in agricultural science and any corresponding research, their current knowledge level, and their expectations for a rigorous program of this nature.

*Note: 4H, FFA competition, or any official uniform or dress is not necessary.*

**Semifinalists should anticipate being onsite at least 2 hours.**

**The use of electronic devices (cell phones, tablets, projectors, etc.) is prohibited during all parts of the interview process.**

# United States

## USDA and FDA Formal Agreement on Regulation of Cultured Meat

*Margaret Rosso Grossman**

### I. Background

Animal agriculture has significant environmental effects.[1] Raising animals and their feed requires large expanses of land. US data from a 2012 land-use survey indicated that livestock grazed on almost 800 million acres (almost 324 million hectares, 35% of US land): permanent grassland pasture and range (655 million acres), cropland pasture (13 million acres), and forest grazing land (130 million acres). In addition, more than 200 million cropland acres produced feed crops.[2] Production of livestock and feed contributes greenhouse gas emissions[3] and odor pollution, causes water pollution, consumes fresh water, contributes to antibiotic resistance, and raises ethical issues.

For ethical, health, or other reasons, some consumers choose vegetarian food, including 'veggie burgers' and plant-based 'meat' proteins.[4] For consumers who prefer animal proteins, however, cellular agriculture may offer innovative proteins that resemble traditional products of livestock, poultry, and fish. As researchers noted,

> the desire to eat meat and animal-derived foods has led to the emergence of cellular agriculture, which aims to produce animal proteins using fewer animals and less animal-derived material than the current livestock industry, by utilising culturing techniques. This approach aims to marry a consumer desire to eat meat with the drive to ensure global food security, a nutritious diet, and reduce the environmental burden of food production.[5]

Cellular agriculture involves two main production methods. Tissue engineering-based production results in cellular agriculture products including meat, poultry, and fish, with the goal of producing products that are biologically equivalent to traditional livestock products. These products are called clean meat, cultured meat, lab-grown meat, *in vitro* meat, or perhaps more accurately 'artificial muscle proteins.'[6] Fermentation-based (or protein-based) production creates acellular agricultural products, including milk and egg proteins and leather.[7]

In a report on future products of biotechnology, the National Academies of Sciences, Engineering, and Medicine identified products derived from animal cell culture among emerging trends and products of biotechnology, and noted that products like cowless meat (and leather) were under development

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1 For details see Scott Schulman, *From Farm-to-Table to Lab-to-Table*, 33(1) Natural Resources & Environment 31-35, at 31-33 (2018).

2 Daniel P. Bigelow & Allison Borchers, Major Uses of Land in the United States, 2012, at 5, 24 (ERS, USDA, EIB 178, 2017). Not all feed crops are used for feed, and some are exported. The 2017 Census of Agriculture indicates that total sales of cattle and calves (not including milk) were more than $77 billion. As of 31 December 2017, the Census estimated the US beef cattle inventory at 93.6 million. National Agricultural Statistics Service, USDA, 2017 Census of Agriculture, Vol. 1, United States Data, Tables 2 & 16, at 10, 22 (Apr. 2019).

3 A recent report indicated that beef is especially resource intensive. It causes greenhouse gas emissions through both methane emissions during production and changes in land use for pasture. Richard Waite et al., 6 Pressing Questions About Beef and Climate Change, Answered (8 Apr. 2019), link from World Resources Institute, <https://www.wri.org>.

4 Plant-based 'meats' are not the subject of this update. Labels for these products are controversial. E.g., for the EU, see Daniel Boffey, *'Veggie discs' to replace veggie burgers in EU crackdown on food labels,* The Guardian (4 Apr. 2019) (discussing proposed new labeling rules).

5 Neil Stephens et al., *Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture*, 78 Trends in Food Science & Technology 155-166, at 156 (2018). Not everyone agrees that 'the production of artificial meat will have a low carbon footprint.' Jean-François Hocquette, *Is in vitro meat the solution for the future?*, 120 Meat Science 167-176, at 172 (2016).

6 Hocquette, *supra* note 5, at 169; Stephens et al., *supra* note 5, at 157.

7 Stephens et al., *supra* note 5, at 157; Monica Saavoss, *How Might Cellular Agriculture Impact the Livestock, Dairy, and Poultry Industries?*, 34(1) Choices 1-6, at 1 (2019).

with early-stage concepts and 'high growth potential.'[8] Indeed, some predict that lab-grown meat will be marketed to consumers within five years.[9] In recent years, Memphis Meats introduced a meatball, as well as chicken and duck patties; Aleph Farms, a thin steak; Modern Meadow, dehydrated steak chips; and Finless Foods, a fish patty. Major agricultural corporations, including Cargill and Tyson, have invested in the technology.[10]

Bill Gates, of the Gates Foundation, identified lab-grown meat as one of 10 Breakthrough Technologies for 2019. He stated that lab-grown meat improves quality of life. It 'isn't about feeding more people, ... it's about making meat better. It lets us provide for a growing and wealthier world without contributing to deforestation or emitting methane. It also allows us to enjoy hamburgers without killing any animals.'[11]

## II. Regulation

Both in the US and the EU, researchers have insisted that clear regulatory requirements should govern production and marketing of cultured meat.[12] In the US, it seems evident that a federally-established national regulatory standard must govern cultured meat, which will be transported in interstate commerce.[13] A number of regulatory issues exist, including safety of cultured meat products, regulation of production facilities, labeling and food fraud, and use of non-livestock species for cellular agriculture.[14]

A threshold issue, of course, is which government agency should govern these products. Some argue that USDA should 'regulate lab-grown meat because it is in the best position to get it on the market quickly, safely, and in a manner appealing to consumers.'[15] USDA regulatory authority already applies to meat, and USDA's Food Safety and Inspection Service (FSIS) inspects meat and meat facilities. It might also be argued, however, that the FDA's authority to govern food additives or to regulate genetically modified animals could apply.[16]

Regulatory decisions may affect the traditional meat industry, and livestock organizations have helped to trigger agency attention to cultured meat. For example, in February 2018, the US Cattlemen's Association, a lobbying organization, petitioned the USDA's FSIS for a regulation that would require clear labeling and identification for 'beef' products not derived from cattle.[17] The Association asked USDA to define meat as 'the tissue or flesh of animals that have been harvested in the traditional manner.'[18] This petition may have triggered agency consideration of cultured meat. In fact, both the FDA and the USDA have expressed interest in resolving food safety and regulatory issues connected with cultured meat.

In June 2018, the FDA issued a statement about cultured food products, referring to 'development of products that are intended to resemble conventional meat, poultry and seafood ... generally made from cells collected from animals that are multiplied using non-traditional food technologies.'[19] The FDA as-

8 National Academies of Sciences, Engineering, and Medicine, Preparing for Future Products of Biotechnology, at 53-54 (2017). NASEM viewed these products as 'contained use,' rather than designed for release in the environment.

9 Saavoss, *supra* note 7, at 1.

10 Stephens et al., *supra* note 5, at 156; Saavoss, *supra* note 7, at 1-2.

11 Bill Gates, What the plow and lab-grown meat tell us about innovation (27 Feb. 2019), <https://www.gatesnotes.com/About-Bill-Gates/MIT-Technology-Review>. The MIT Technology Review invited Gates to help choose breakthrough technologies; interestingly, he identified the plow, which has improved quantity of life by helping to feed more people.

12 See, e.g., Alan Sachs & Sarah Kettenmann, *A Burger by Any Other Name: Regulatory Challenges and Opportunities for Cell-Cultured Meat*, 15(2) SciTech Lawyer 19-23 (Winter 2019); Ludivine Petetin, *Frankenburgers, Risks and Approval*, 5(2) European Journal of Risk Regulation 168-186 (2014); Zachary Schneider, Comment, *In Vitro Meat: Space Travel, Cannibalism, and Federal Regulation*, 50(3) Houston Law Review 991-1025 (2013).

13 Schneider, *supra* note 12, at 1014 (recommending regulatory approaches, at 1013-1022).

14 Stephens et al., *supra* note 5, at 162-163.

15 Schulman, *supra* note 1, at 31.

16 *Id*. at 34. USDA, rather than FDA, governs most meat products, but FDA authorizes GM animals under its new animal drug process.

17 US Cattlemen's Association, Press Release, U.S. Cattlemen's Association: Meat is Meat, Not a Science Project (9 Feb. 2018), <https://mailchi.mp/uscattlemen/senate-eld-letter-1817769>. The Association brings the cattle industry's voice to Washington DC and advises policy makers.

18 US Cattlemen's Association, Petition for the Imposition of Beef and Meat Labeling Requirements: To Exclude Products Not Derived Directly from Animals Raised and Slaughtered from the Definition of 'Beef' and 'Meat,' link from <https://www.uscattlemen.org>.

19 FDA, Press Announcement, Statement from FDA Commissioner Scott Gottlieb, M.D. and FDA Deputy Commissioner Anna Abram on emerging food innovation, 'cultured' food products (15 June 2018), <https://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm610869.htm>.

serted regulatory jurisdiction over these products under the Food, Drug, and Cosmetic Act, and the USDA responded by emphasizing its own responsibility for products marketed as meat and its willingness to work with FDA.[20] Thereafter, FDA held a public meeting to discuss cultured meats and related products from animal cell culture technology, with a focus on food safety and related issues.[21] USDA (FSIS) and FDA then held a joint meeting, with participation from stakeholders, to discuss animal cell-cultured food technology.[22]

In November 2018, USDA and FDA issued a joint statement on the regulation of cell-cultured food products.[23] The two agencies agreed to oversee cell-cultured food products under a joint regulatory framework. This framework, the agencies asserted, 'will leverage both the FDA's experience regulating cell-culture technology and living biosystems and the USDA's expertise in regulating livestock and poultry products for human consumption.' Moreover, the agencies believed that the regulatory framework could be implemented under existing statutory authority, with no new federal legislation.

## III. USDA and FDA Formal Agreement

Most recently, in March 2019, USDA and FDA issued a Formal Agreement on regulating cell-cultured food intended for human consumption.[24] The Agreement applies to 'the oversight of human food produced using animal cell culture technology, derived from cell lines of USDA-amenable species and required to bear a USDA mark of inspection' (para 1).[25] Shared regulation will encourage innovation while helping to ensure that these products are safe and labeled accurately. The document represents an on-going process, with a commitment to refine details of agency responsibilities and to identify possible statutory or regulatory changes required for effective oversight (para 2).[26]

After outlining relevant statutory authority (para 3),[27] the Agreement sets out responsibilities of FDA and USDA, acting through FSIS. The agencies agreed to share information and to collaborate (para 4). Each agency will conduct inspections, take enforcement actions for activities within its responsibilities, and develop additional requirements. The agencies agreed to develop a more detailed framework, establish joint principles for labeling and product claims to ensure consistency and transparency, and cooperate in investigating food safety issues from cell-cultured products.

In essence, FDA will govern the early stages of cultured-meat production: cell collection, cell banks, and cell growth and differentiation. The agency will issue guidance documents or regulations to govern these early stages of production. FDA will ensure that regulated facilities are registered, that entities meet FDA requirements for food manufacturing, and that cell cultures are safe and not adulterated. The agency will inspect facilities and enforce its applicable laws and regulations (para 4A).

Oversight will move from the FDA to FSIS at the cell harvest stage, when FDA will provide information and other help to transfer regulatory oversight and to ensure that 'harvested cells are eligible to be processed into meat or poultry products that bear the USDA mark of inspection.' Thereafter, FSIS will govern production and labeling of food products derived from livestock and poultry cells. Under its regulations, FSIS will inspect facilities that harvest cells, process cells into food for humans, or process and package food products to ensure that products are 'safe, unadulterated, wholesome and properly la-

20 Helena Bottemiller Evich, Welcome to the turf battle over lab-grown meat (15 June 2018), <https://www.politico.com/story/2018/06/15/lab-grown-meat-feds-turf-battle-629774>.

21 Announced at 83 Federal Register [Fed. Reg.] 28,238-28,240 (18 June 2018). Information about the meeting, including a transcript, is at <https://www.fda.gov/Food/NewsEvents/WorkshopsMeetingsConferences/ucm610138.htm> (13 Aug. 2018).

22 Announced at 83 Fed. Reg. 46,476-46,478 (13 Sept. 2018). Presentations and recordings are at <https://www.fda.gov/Food/NewsEvents/WorkshopsMeetingsConferences/ucm619874.htm> (6 Nov. 2018).

23 USDA, Press Release, Statement from USDA Secretary Perdue and FDA Commissioner Gottlieb on the Regulation of Cell-Cultured Food Products from Cell Lines of Livestock and Poultry (No. 0248.18, 16 Nov. 2018), <https://www.usda.gov/media/press-releases/2018/11/16/statement-usda-secretary-perdue-and-fda-commissioner-gottlieb>.

24 USDA & FDA, Press Release, USDA and FDA Announce a Formal Agreement to Regulate Cell-Cultured Food Products from Cell Lines of Livestock and Poultry (No. 0027.19, 7 Mar. 2019).

25 FDA & USDA, Formal Agreement between the U.S. Department of Health and Human Services Food and Drug Administration and U.S. Department of Agriculture Office of Food Safety (7 Mar. 2019), <http://www.fsis.usda.gov/formalagreement>.

26 This seems to retreat from the November 2018 suggestion that the agencies could regulate cultured meat without new legislation.

27 For FDA: Federal Food, Drug, and Cosmetic Act, 21 USC §§ 301-399, supplemented by the Food Safety Modernization Act, 2011, 21 USC §§ 2201-2252; Public Health Service Act, 42 USC §§ 201-300mm-61; Fair Packaging and Labeling Act, 15 USC §§ 1451-1461. For USDA FSIS: Federal Meat Inspection Act, 21 USC §§ 601-695; Poultry Products Inspection Act, 21 USC §§ 451-471; Egg Products Inspection Act, 21 USC §§ 1031-1056.

beled.' Labels must be pre-approved and verified (para 4B).

The National Cattlemen's Beef Association praised the Formal Agreement, which 'solidifies USDA's lead oversight role in the production and labeling of lab-grown fake meat products, ... [with labels] subject to USDA's pre-approval and verification process.'[28] Yet the producer-directed trade association noted the lack of specific details and outlined some questions that the Agreement left unanswered, including the role of antibiotics, food safety risks at scale, safety of finished product, equivalence (or not) to 'real beef,' and the role of independent scientific analysis.[29] Another organization, the US Cattlemen's Association, again expressed concern about labels for cultured meat. Although applauding FSIS labeling authority, the association insisted that the terms 'meat' and 'beef' should be reserved for 'products derived exclusively from the flesh of a bovine animal harvested in the traditional manner.' FSIS should develop a meat inspection stamp with a new format and color, the association asserted; to avoid 'intentional consumer confusion,' purple USDA meat inspection stamps should not appear on cell-cultured products.[30]

## IV. Regulatory Issues

The Formal Agreement is a starting point and leaves some open questions. For example, the agencies do not indicate whether they will use existing regulatory and notification procedures or enact new regulations. Researchers have noted that neither the Federal Meat Inspection Act nor FSIS regulations address the regulatory status of cultured meats, but these measures could be interpreted to apply. FSIS inspection rules, which govern livestock carcasses, seem less likely to authorize inspection of facilities that produce the meat.[31] FDA authority to regulate food safety and sanitation, as well as food ingredients (for example, food additives), may apply for some products.[32] Although the June 2018 FDA statement included seafood among cultured products, the Formal Agreement does not mention seafood, currently regulated by FDA.[33]

Labels for cultured meats are likely to be contentious. The Agreement assigns the preapproval and verification of labels to USDA, which may develop labeling requirements for cultured meat. (para B4, 5) Recent USDA regulations require GM foods to carry labels that identify those foods as 'bioengineered,' and some cultured meat may trigger these regulations.[34] That is, development of cellular meat sometimes involves a genetically-modified cell line or genetically modified ingredients for fermentation, and some laboratories are now using genetic modification.[35]

Moreover, USDA approval of labels that use the term 'meat' will conflict with some state laws. A few states have passed (or proposed) laws that prohibit the term 'meat' on labels for cultured meat. For example, Missouri enacted a law that would define meat as any 'edible portion of livestock, poultry ... carcass or part thereof,' and meat product as 'any-

28 National Cattlemen's Beef Association, Press Release, Formal Lab-Grown Fake Meat Agreement is 'What Consumers Deserve' (7 Mar. 2019), <http://www.beefusa.org/newsreleases.aspx?NewsID=6901>.

29 National Cattlemen's Beef Association, Fake Meat Facts (Mar. 2019), <http://www.beefusa.org/CMDocs/BeefUSA/OnePager_FakeMeatFactsFormalAgreement.pdf>.

30 US Cattlemen's Association, Press Release, U.S. Cattlemen's Association Responds to Formal Agreement to Regulate Cell-cultured Food Products (7 Mar. 2019) (both quotations), <https://mailchi.mp/uscattlemen/truth-in-labeling-1818249?e=[UNIQID]>. See *supra* note 18.

31 Sachs & Kettenmann, *supra* note 12, at 20-21.

32 *Id*. at 21. FDA authority does not apply to meat and poultry products governed by USDA. Food additives are approved by a petition process, and some additives, scientifically evaluated as safe, may qualify for a GRAS (Generally Recognized as Safe) determination. On FDA's GRAS rules, see Margaret Rosso Grossman, *US FDA Enacts Final Rule for GRAS Substances*, 12(2) EFFL 169-172 (2017).

33 In March 2018, FDA lifted its import ban on the AquaBounty genetically modified salmon, approved under the FDA's new animal drug regulations. Final regulations under the National Bioengineered Food Disclosure Standard will satisfy the congressional requirement of labeling for AquAdvantage salmon. FDA, Press Release, Statement from FDA Commissioner Scott Gottlieb, M.D., on continued efforts to advance safe biotechnology innovations, and the deactivation of an import alert on genetically engineered salmon (8 Mar. 2019).

34 See Margaret Rosso Grossman, *Labeling Bioengineered Food in the United States: Final Regulations from the US Department of Agriculture*, 14(2) EFFL 142-151 (2019). A related issue is regulatory, because FDA governs GM animals (e.g., AquAdvantage salmon) under its regulations for new animal drugs. Its draft guidance document, however, applies to animals (rather than animal products) with intentionally altered DNA. FDA, Draft Guidance for Industry #187, Regulation of Intentionally Altered Genomic DNA in Animals (Jan. 2017, to be finalized in 2019), <https://www.fda.gov/downloads/AnimalVeterinary/GuidanceComplianceEnforcement/GuidanceforIndustry/UCM113903.pdf>.

35 Stephens et al., *supra* note 5, at 157 (noting, at 162, that 'the potential for genetically modifying the cells is a key issue of contestation within the field with several laboratories pursuing this route'). Petetin, *supra* note 12, assumes that cellular meat does not involve genetic modification.

thing containing meat ... derived, in whole or in part, from livestock [or] poultry,' with criminal penalties for misrepresenting a product as meat.[36] A plant-based meat corporation and other plaintiffs with interest in cultured meat challenged the constitutionality of the law, and the parties are now in court-ordered mediation.[37]

Significantly, USDA labeling requirements are likely to preempt state law restrictions. Preemption provisions in the Federal Meat Inspection Act and the Poultry Products Inspection Act prescribe that states cannot impose marking, labeling (and other) requirements that are 'in addition to, or different than' requirements under federal law.[38]

## V. Conclusion

Cultured meat may eventually help to meet social and environmental goals by reducing livestock production, and it may play a role in addressing food security issues.[39] In addition to possible environmental benefits, cultured meat may offer health benefits (for example, no antibiotics used in production, no risk of fecal contamination, perhaps fewer saturated fats). But risks are possible, too, including bacterial contamination in the production process.[40]

Successful development of a cultured-meat industry is likely to affect the livestock industry, although effects will depend on the extent of production. For example, wide availability (and consumer acceptance) of cultured beef products may reduce demand for traditional beef.[41] If the industry is to succeed, consumer acceptance will be critical. A recent study indicated that a majority of US participants were not familiar with clean (that is, cultured) meat, but almost 75% were somewhat, moderately, very, or extremely likely to purchase clean meat.[42] Consumer acceptance will require education and high-quality products.

The Formal Agreement between FDA and USDA is an important starting point in the regulation of protein from cultured meat. In April 2019, a bill introduced in the US Senate would clarify oversight and jurisdiction for food safety inspection set out in the Formal Agreement. If enacted, the proposed Cell-Cultured Meat and Poultry Regulation Act of 2019 would require the agencies to enter a binding agreement on jurisdiction and to promulgate regulations that set out food safety requirements for cell-cultured meat. The bill was referred to the Senate Committee on Agriculture, Nutrition, and Forestry; as of August 2019 no further action has been taken.[43]

Although large-scale production of cultured meat is unlikely to occur in the near future, some small-scale production exists, and a clear regulatory system is needed. Regulation and other government policies, as well as availability of funding, will influence the cultured-meat industry. At present, '[c]ultured meat remains an early stage technology with a diverse range of potential benefits and a wide set of challenges.'[44] Whether these challenges will be met and the benefits achieved will depend in part on appropriate regulation and consumer acceptance.

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36 Mo. Rev. Stat. §§ 265.300, 265.494(7), amended in 2018. See Dan Flynn, The ban against lab-grown food using 'meat' on the label grows to 7 states, Food Safety News (5 Apr. 2019), <https://www.foodsafetynews.com/2019/04/the-ban-against-lab-grown-food-using-meat-on-the-label-grows-to-7-states/>. Other states include Arkansas, Mississippi, Montana, North Dakota, South Dakota, and Wyoming; similar legislation has been proposed in additional states.

37 Turtle Island Foods v. Richardson, Case No. 2:18-cv-04173-FJG (WD Mo., 27 Aug. 2018). An August 2019 order referred the case to mediation, <https://www.courtlistener.com/docket/7750070/turtle-island-foods-spc-v-richardson/>.

38 21 USC § 467e; 21 USC § 678.

39 Stephens et al., *supra* note 5, at 164. For a Dutch viewpoint, see Isabel Michelotti, Sappig stukje kweekvlees, De Telegraaf (28 July 2017) (quoting a scientist who predicts that in 25 years, consumers will eat cultured meat (*kweekvlees*), rather than meat from animals).

40 Saavoss, *supra* note 7, at 3.

41 *Id*. at 4-5. See Carsten Gerhardt et al., How Will Cultured Meat and Meat Alternatives Disrupt the Agricultural and Food Industry? (ATKearney, June 2019). The report predicts that '[i]n 20 years, only 40% of global meat consumption will still come from conventional meat sources.'

42 Survey participants (generally urban and well-educated) in China and India were even more likely to purchase clean meat. Christopher Bryant et al., *A Survey of Consumer Perceptions of Plant-Based and Clean Meat in the USA, India, and China*, 3 Frontiers in Sustainable Food Systems, art 11, at 4 (Feb. 2019).

43 S. 1056, 116th Congress (2019-2020), introduced 4 April 2019. The bill is short and would also amend the Federal Meat Inspection Act and Poultry Products Inspection Act to include language referring to cell-cultured food products. Many bills are introduced in Congress, and enactment is not certain.

44 Stephens et al., *supra* note 5, at 163, 164.

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# Liquid biofuels from food waste: Current trends, prospect and limitation

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ABSTRACT

Depletion of fossil fuels, environmental damage due to pollution and energy security have intensified research on alternative liquid biofuels. A major portion of municipal solid waste is food waste. Huge quantities of food waste is generated worldwide and currently its disposal is becoming a challenge. Food waste contain carbohydrates, lipids, phosphates, vitamins and amino acids. Carbohydrate, lipid and carbon containing materials present in food waste can be converted to bioethanol, biodiesel and biooil. Lipid extracted from food waste is converted to biodiesel in 95–97% yield. On the other hand, 92–96% bioethanol obtained by fermentation of food waste. Along this line, pyrolysis of food waste can be performed to obtain biooil and biochar. In this paper, technical feasibility, prospects and policies for liquid biofuel preparation from food waste was evaluated. Also, limitations of using food waste as a resource for biofuel production is discussed.



**Contents**



## 1. Introduction

Researchers are investigating new and alternative liquid biofuels for various reasons such as (i) depletion of fossil fuels, (ii) increasing demand for liquid fuels, (iii) energy security and less dependency on politically unstable middle east countries and (iv) environmental pollution [1]. In this regard, biofuels are becoming

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1364-0321/

increasingly important as alternative energy source. Different biofuels such as bioethanol and biodiesel are used as substitute to diesel fuel and gasoline in many countries [2–10]. Furthermore, bioethanol and biodiesel can be used as blend along with gasoline and petro–diesel. According to reports by Food and Agricultural Organization of the United Nations approximately 1.3 billion tons of food waste is discarded globally without any further use [11]. These food wastes almost account to one third of the worldwide food produced for the human consumption. Food waste generated in developing Asian countries is expected to rise further in the upcoming years because of rapid economic expansion and continuous population growth. For instance, from 2005 to 2025 food waste produced in the urban stettlements of the Asian economies is all set to rise from 278 to 416 million tons [12]. Along this line, worldwide 1300 million tonnes of food waste is generated; whereas, Asia and South-eastern Asia produces 278 and 79.3 million tonnes of food waste [11,12]. Asian economic giant China alone produces 82.8 million tonnes of food waste [13]. Fig. 1. shows the present data on food waste generation in Asia-Pacific countries [14].

In most of the countries generated food waste is disposed at landfills along with municipal solid wastes. For instance, in Hong Kong in 2012, around 9278 t per day of municipal solid waste was disposed in landfills [15,16]. Out of this total municipal waste, around 36–40% was food waste or biobased waste [15,16]. Food waste is considered as the largest category of municipal solid waste that is disposed in landfills. This is causing world's mounting food waste disposal problem which is further encouraged by throwaway culture. This practice of disposing food waste in landfills is creating many problems in public life such as bad odor, air pollution, and leaching. Landfills are known to generate carbon dioxide, methane and other toxic gaseous substances [15,16]. Specifically, methane is the most abundant greenhouse gas generated from landfills. Rainfall event results in leaching of undesirable leachate which pose risk to public health. In addition, landfills also occupy a lot of space which is further a constraint for metropolitan cities where land is costly and needed for infrastructure development. To circumvent these problems recyling of food waste is necessary.

To a large extent, development of sustainable food waste valorization is needed to solve the waste disposal and environmental problems. At present, many conventional food waste valorization methods exists to recycle food wastes such as incineration, anaerobic digestion, and processing it as fish and animal feed purposes [15,16]. Nevertheless, conversion of food waste to potential liquid biofuels is important; and it is currently being investigated by many researchers as they can be used as fuels in pure form or as blend in existing diesel engines [17–20].

Presently, biofuels are produced from edible feedstocks. Feedstocks contribute significantly (around 80–90%) towards the total cost of biofuels [21]. Thus, use of edible feedstocks make biofuels costly. Alternatively, non-edible feedstocks are extensively investigated for biofuel production in academia and industry [22–28]. There is also a growing food vs fuel debate among the concerned mermbers of the civil societies and stake holders [29–31]. Many critics are also arguing that increased in land use for growing biofuel crops will result in shortage of land, water and other resources for growing food crops which will contribute towards food shortage [29–31]. However, biofuels can be produced in alternative ways by using wastes as non-edible resources. In this regard, waste cooking oil and food wastes can be utilized to produce biofuels without using land availabile for growing food crops [32–34]. Further, recycling food wastes for biofuel production will also avoid the ongoing food vs fuel debate.

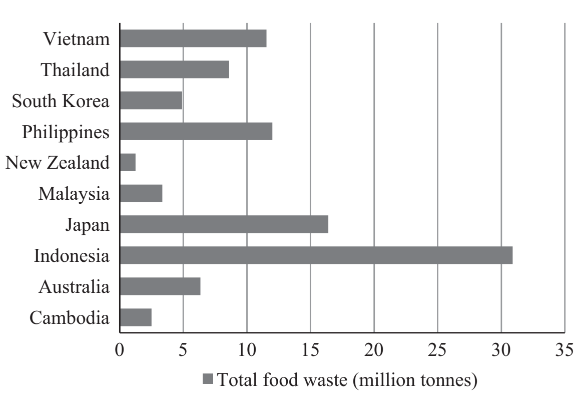



**Fig.1.** Food waste produced in Asian and Asia-Pacific countries [14].

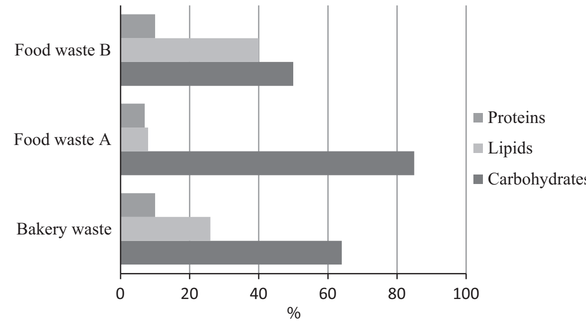



**Fig.2.** Amount of protein, lipid, and carbohydrate present in bakery waste. Sample A and B are mixed food waste obtained from same canteen in different days [38,39].

Food waste mainly composed of (1) rotten fruits and vegetables, (2) fish and poultry organs, intestine, meat trimmings and other residues, (3) fruits and vegetable peelings, (4) meat, fish, shellfish shells, bones, (5) food fats, sauces, condiments, (6) soup pulp, herbal medicinal pulp, (7) egg shells, cheeses, ice cream, yogurts, (8) tea leaves, teabags, coffee grounds, (9) bread, cakes, biscuits, desserts, jam (10) cereals of all types e.g. rice, noodles, oats, (11) plate scrapings and leftover of cooked food, (12) BBQ raw or cooked leftovers, and (13) different pet foods [15,16]. Food waste is considered a zero value resource since it is discarded without any use. Chemically, food wastes contain lipid, carbohydrate, amino acid, phosphate, vitamins and other carbon containg substances (Fig. 2) [18–20]. Lipid derived from food wastes can be conveted to biodiesel [18–19]. Additionally, complex carbohydrate such as cellulose and starch in food wastes can be hydrolyzed into small sugars viz. glucose and fructose. Subsequently, these sugars can be fermented to bioethanol [18–20]. There are also reports about pyrolysis of the food waste into biooil [35–37]. Liu et al. have reviewed biotechnological production of ethanol, methane and hydrogen from food waste [14]. Whereas, Pham et al. reviewed the use of different technologies such as biological (viz. anaerobic digestion and fermentation), thermal and thermochemical (viz. incineration, pyrolysis, gasification and hydrothermal oxidation) for conversion of food waste to energy. In this review, technical aspects of the preparation of liquid biofuels from food waste is discussed. Industrial viability of selected processes are evaluated. In addition, policies, prospects and limitations of using food waste as a no-value resource for biofuel production is described.

## 2. Production of liquid biofuels from food waste

Food waste disposal is increasingly becoming challenging. Most of these food wastes are dumped directly in landfills everyday. Biochemical decomposition of food waste results in unpleasant smell and formation of unhealthy degraded products [15,16]. To circumvent this problem, several countries have formulated future plans to "use less" and "waste less" to develop an ecofriendly society by minimizing food waste generation [15,16]. Although, dumping of food waste in landfills is regarded as one of the most easier and economic way of disposal; it is unsustainable and environmentally unfriendly. In this context, better management of food products at food industries and eateries level will certainly help to bring down the amounts of food waste produced. Currently, there are various technologies available for the utilization of food wastes. Hitherto, conventional techniques viz. (i) composting of food waste, (ii) preparation of animal feed, and (iii) preparation of biogas production are adopted for food waste valorization [15,16]. However, these technologies are used to convert food waste to gaseous fuels and not liquid fuel. Cutting edge valorization technologies are requied for the efficient production of liquid biofuels from food waste [34]. In this regard, development of green catalytic processes are becoming attractive. Along this line, different chemical and enzymatic methods can be used for food waste valorization. Furthermore, cascade reactions such as chemo-enzymatic, multistep-chemocatalytic and multistep-enzymatic can also be tried for food waste valorization. These cascade reactions are particularly promising as the target products can be achived directly without isolation and purification of intermediates in a single solvent system [40,41]. In this context, researchers are converting different kinds of food wastes viz. bread, wheat, rice, meat, vegetable peelings and mixed food wastes to liquid biofuels [17–20]. For instance, bakery waste and mixed food waste can be hydrolyzed by bi-enzymatic systems to obtain crude hydrolysate containing lipids, carbohydrates, amino acids and phosphates [38,39]. Carbohydrate and lipid portion of the hydrolysate can be converted to bioethanol and biodiesel, respectively using chemo- and bio-catalytic methods (Fig. 3) [18,19]. In addition, food waste can be directly subjected to pyrolysis to obtain bio-oil (Fig.3).

### 2.1. Biodiesel

Biodiesel is used as a fuel in Europe, US and many other countries. Chemically, biodiesel is composed of fatty acid methyl esters (FAME). Biodiesel contain both saturated and unsaturated fatty acid methyl esters depending on source of the feedstocks viz. plant oils, animal fats and waste oils. Edible plant oils viz. sunflower, palm, soybean, rapeseed and other oils are generally used for biodiesel production. Biodiesel obtained from edible oils are costly; therefore, the current biodiesel cost is higher than petroleum fuels. In this regard, already a food vs fuel debate is underway. Thus, there is a need to use low-cost and non-edible oils for biodiesel production. Along this line, non-edible plant oils such as Jatropha, Pongamia, Mohua, and others are already investigated for biodiesel production [24–27]. However, land, water, fertilizer, manpower and other resources are required for non-edible oil plant cultivation. Some authors are terming the growing of biofuel plants as a crime against humanity [29–31]. As an alternative, food waste and waste cooking oil can be used for biodiesel production since: (i) it is a low-cost and no-value resource and (ii) it is non-competitive with edible food stuffs [14, 20–23].

The production of biodiesel from food waste requires extraction of lipids. Firstly, the food waste is mixed with water (typically 100 g of food waste in 1 l of water) to make slurry then it can be mixed vigorously with non-polar organic solvents viz. n-hexane and diethyl ether. This step is not compulsory but can be done. Afterwards, the obtained mixture is then transferred into a separating funnel. The organic layer is separated and evaporated under reduced pressure to obtain the organic solvent-free lipid. Yang et al. extracted oil from noodle waste. Typically, 100 g of the instant noodle residue was boiled with one litre water. Subsequently, the oil was extracted using 500 ml of n-hexane. Using this method 5 ml of oil was isolated from 100 g of noodle waste [42,43]. Alternatively, fungal hydrolysis of food waste using bi-enzymatic catalytic system containing *Aspergillus awamori* and *Aspergillus oryzae* can be carried out to separate the lipid, and food hydrolysate rich in carbohydrate, amino acids and phosphate [38,39]. After hydrolysis the obtained hydrolytic mixture is subjected to centrifugation to separate the crude lipid from the food hydrolysate. The obtained crude lipid is then heated to 100 °C to obtain the water free lipid [18,19]. Additionally, lipid can be extracted by using soxhlet extraction which is more efficient than the conventional extraction methods. Along this line, supercritical fluids are extensively utilized as solvents for lipid extraction from natural herbs and as reaction mediums to perform chemical and enzymatic reactions [40,41].

Particularly, supercritical carbon dioxide ($scCO_2$) is used for the extraction oils. This method can be tried for the extraction of lipid from food wastes. Lipid extracted using $scCO_2$ is not contaminated with organic solvents unlike the conventional extraction processes. Moreover, $scCO_2$ extraction process can be optimized by adjusting pressure and temperature [44]. Thus, lipid obtained is clean and can be directly used for biodiesel production. Different lipid extraction processes are summarized in Fig. 4.

Lipid obtained from food waste is first tested to determine the acid value and moisture content. Base catalyzed transesterification using KOH and NaOH as catalysts is reported for the biodiesel preparation for low free fatty acid (FFA) containing feedstocks [8]. Additionally, acid catalyzed transesterification can be carried out for biodiesel preparation. For high FFA containing feedstock two-step reaction is carried out. In the first step, acid catalyzed esterification and in some cases base catalyzed pretreatment is required to lower the acid value of lipid feedstocks [8]. After this base

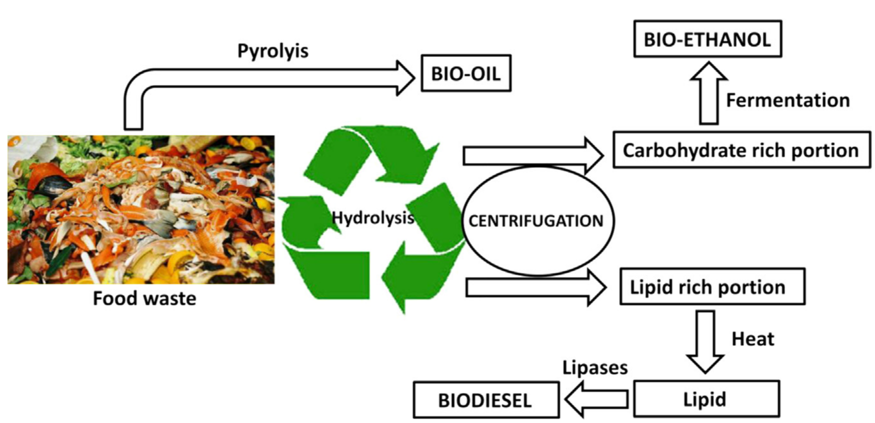



**Fig. 3.** Simultaneous production of biooil, bioethanol and biodiesel from food waste using chemical and biocatalytic methods [18, 19].

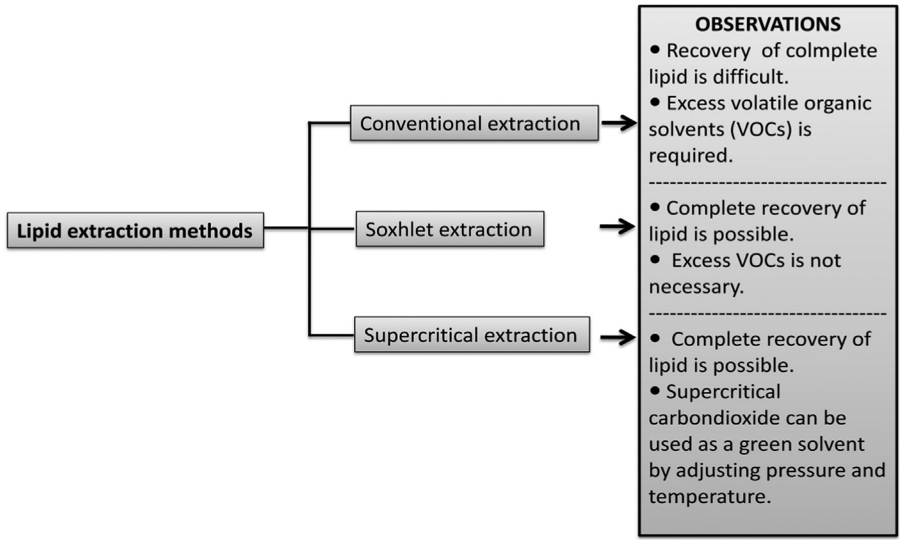
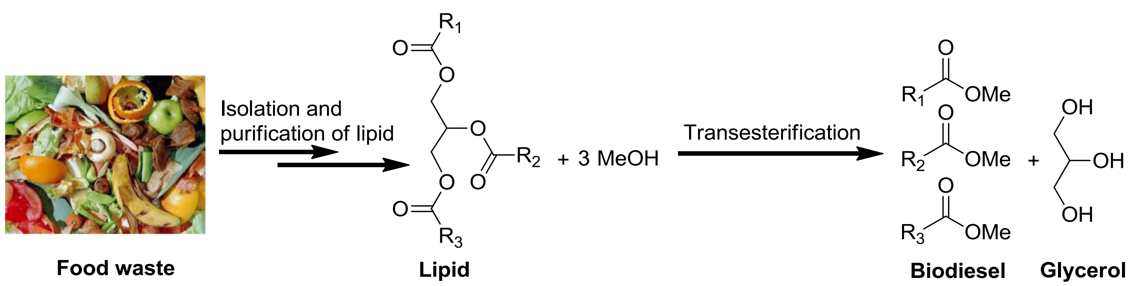



**Fig. 4.** Different extraction methods can be used for the extraction of lipid from food waste.




**Scheme 1.** Isolation and purification of lipid followed by its transesterification to produce biodiesel.

catalyzed transesterification is performed to obtain high yield of biodiesel. Both base and acid catalyzed reactions are affected by moisture content [8]. In presence of water, base catalyzed reaction lead to saponification instead of transesterification. Furthermore, acid catalyzed transesterification lead to hydrolysis in the presence of water. Both acid and base catalyzed reaction require high reaction temepartune. It is a well know fact that acid and base are corrosive and toxic towards the environment.

Enzymes are proteins. Enzymes can be used as an alternative to chemical catalysts for biodiesel synthesis. Lipases are a class of enzymes which are known to catalyze hydrolysis, esterification and transesterification reactions [45,46]. Lipase catalyzed biodiesel production is extensively reported as the reaction can be carried out under mild conditions and no side products are formed [47–51]. Moreover, lipases are moisture tolorent. Both free and immobilized lipases can be used for biodiesel preparation. Immobilized lipases are recovered after transesterification and can be reused for many cycles [47–51].

Acid, base and enzyme catalyzed reactions are reported for the production of biodiesel from food waste (Scheme 1). Yang et al. studied the feasibility of biodiesel synthesis from oil obtained from instant noodle waste. Both KOH and $H_2SO_4$ were used as catalysts for the preparation of biodiesel. Under optimized reaction conditions using KOH (2% w/v) and 1:8 methanol to oil molar ratio 98.5% of biodiesel can be achived at 60 °C in 2 h [42]. Whereas, $H_2SO_4$ (5% v/v) catalyzed reaction gave 97.8% biodiesel in 3 h using 1:6 methanol to oil molar ratio at 80 °C [42]. In addition, Yang et al. also used Novozyme-435 for the transesterification of oil obtained from noodle waste. Four parameters were optimized viz. (i) effect of different alcohols, (ii) oil to alcohol molar ratio, (iii) reaction time, (iv) lipase amount and (v) water content for biodiesel production [43]. Under optimized reaction conditions 95.4% biodiesel yield was achived [43]. Karmee et al. used lipid from food waste for biodiesel preparation. Biodiesel yield 100% was achived in 2 h for KOH catalyzed transesterification at 1:10 M ratio (lipid to methanol) and 60 °C; whereas, in 24 h Novozyme-435 gave 90% biodiesel yield at 1:5 M ratio (lipid to methanol) and 40 °C [52].

### 2.2. Bioethanol

Bioethanol is an important biofuel since it has the potential to replace of gasoline [2]. World bioethanol production increased from 31 billion liters in 2001–39 billion liters in 2006 [53,54]. Worldwide total bioethanol production is expected to rise further to 100 billion liters in 2015 [53, 54]. Around 62% of world ethanol production is contributed by Brazil and the USA [55]. Large scale production of bioethanol is carried out using edible materials such as sugarcane and corn. This makes bioethanol costly as compared to the cost of fossil fuels.

Food wastes such as mixed food waste, wheat-rye bread mashes, kitchen wastes, banana peel, potato peel are recently exploited for bioethanol production (Table 1) [56–77]. Pretreatment of food waste is necessary before enzymatic hydrolysis (Fig. 5). Often autoclave of food wastes is required to prevent microbial contamination [14,20]. Thermal pretreatment lead to degradation of food wastes; therefore, it is avoided. After preatreatment, the food waste is subjected to hydrolysis or saccharification (Fig. 5) [14,20]. Generally, a mixture of α-amylase, β-amylase, and glucoamylase is used for the hydrolysis of starch to small sugar units. The obtained food hydrolysate is subjected to fermentation (Fig. 5) [14,20]. Finally distillation is done to obtain pure ethanol.

**Table 1**
Production of bioethanol from different types of food wastes.

| Type of food waste | Microorganism | Method | Reference |
|---|---|---|---|
| Instant noodle waste | *Saccharomyces cerevisiae* K35 | Simultaneous saccharification and fermentation | [42] |
| Potato peel waste | *Saccharomyces cerevisae var. Bayanus* | Acidic hydrolysis or enzymatic hydrolysis followed by fermentation | [56] |
| Mixed food waste | *Saccharomyces cerevisiae* | Enzymatic hydrolysis followed by fermentation | [61] |
| Household food waste | *Saccharomyces cerevisiae* | Enzymatic liquefaction/saccharification followed by fermentation | [66] |
| Mixed food waste | *Saccharomyces cerevisiae* H058 | Hydrolysis followed by fermentation | [76,77] |
| Banana waste | *Saccharomyces cerevisiae* | Enzymatic hydrolysis followed by fermentation | [78] |

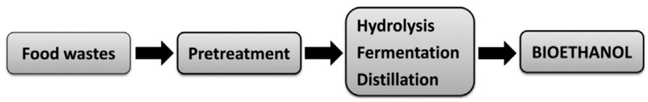



**Fig. 5.** A schematic representation of different steps leading to bioethanol production.

Ethanol was produced from food waste hydrolysate using *Saccharomyces cerevisiae* H058 strain [76,77]. Starch residue from instant noodle waste was converted to bioethanol using *S. cerevisiae* K35 by simultaneous saccharification and fermentation process. Optimization of fermentation was carried out to obtain 96.8% ethanol conversion in 36 h [42,43]. Along this line, potato peel waste known to contain substantial amount of carbohydrate [56]. Potato peel was hydrolyzed using enzymes and acid. Subsequently, the obtained sugar was fermented using *S. cerevisae var. bayanus* to obtain 7.6 g $L^{-1}$ of ethanol [56]. South Korean food waste is rich in carbohydrate (~65%) [61]. Enzymatic hydrolysis and fermentation was carried out using carbohydrase and *S. cerevisiae.* When hydrolysis and fermentation were carried out separately ethanol yield was 0.43 g ethanol/g total solids; whereas, during simultaneous saccharification and fermentation 0.31 g ethanol/g total solids ethanol yield was obtained [61].

Banana waste has the potential to produce ethanol. The authors evaluated separation of ethanol from banana waste using pervaporation using hollow membrane [78]. Response surface methodology was applied to optimize the conditions of enzymatic saccharification and ethanol fermentation from food waste [62]. The model predicted that maximum concentration of reducing sugar is 117.0 g reducing sugar/L and ethanol is 57.6 g ethanol/L; whereas, experimental results showed that 120.1 g reducing sugar/L and 57.5 g thanol/L can be obtained. Ethanol production from household food waste was carried out [62]. Liquefaction/saccharification was performed which reduced the viscosity of the substrate significantly [66]. This step lead to high yield of ethanol (107.58 g/kg dry material) [66].

### 2.3. Biooil

Biooil is a liquid fuel with dark brown color. Biooil has the potential to substitute conventional petroleum fuels. Currently, several research groups are engaged in developing technologies for the production of biooils. Biooils can be prepared from biomass viz. stich grass, agricultural residues, municipal biowastes and forestry wastes. Pyrolysis is used as a method for the production of biooil. Production of biooil by flash pyrolysis is currently investigated in industrial scale. There are many limitations of biooils viz. (i) poor thermal stability, (ii) poor fuel proterties and (iii) corrosive nature. Unlike biodiesel and bioethanol; so far, biooils are not available commercially in fuel stations. There are few initial reports on the production of biooils from food wastes [35]. For instance, Ahmed and Gupta reported the pyrolysis and gasification of food waste [36]. Balasubramanian et al. reported enzymatic hydrolysis of food waste prior to hydrothermal treatment to produce hydrochars and biooil. Pre-treatment of food waste was carried out using carbohydrase, protease and lipase [79]. The enzymatic pre-treatment improved the yield of hydrochars and bio-oil. Highest bio-oil yield was obtained at 350 °C [79]. The results show that food waste can be potentially used for biooil generation. In this regard, biooil holding NV, Tessenderlo, Belgium is a leading company specializes in conversion of conversion of waste to biooil by fast pyrolysis process [37].

## 3. Economics of biofuel from food waste

Many countries in US, Europe and Asia have formulated economic policies keeping the biofuel based energy demand in mind. In the coming decades, biofuel will be a major driving force for the economic growth of many countries in a similar way development of fossil fuel rich economy happened. There are many economic benefits for biofuel production. Academic investigations using economic tools reveal that biofuels can lower greenhouse gas emissions compared to conventional fuels [80,81]. Furthermore, production of biofuel could reduce dependency on petroleum fuel which may lower the cost of fossil fuels. Biofuel production will also make countries energy independent and this will have a positive impact on economy since there will be less dependecy on politically unstable fossil fuel rich nations.

Two liquid biofuel biodiesel and bioethanol are in the process of replacing diesel and gasoline. Biodiesel and bioethanol from foodwaste as transportation fuels will be benificial. Availability and cost of the starting materials are known to affect the price of biofuels. At present, food waste is labeled as no-cost resource since it is discared without further use. So, from the resource point of view main costs are sorting, transportation and pretreatment of food waste. To the best of knowledge of this author, there are no reports on the techno-economic analysis of viability of food waste based small or medium scale biodiesel and bioethanol plant. A techno-economic study will provide information on (i) design and cost estimation of biofuel plant, (ii) development of the methodology, (iii) real market data, (iv) financial analysis of the production facility and (v) cost of the biofuel [82].

There are also economic disbenifits for biofuel production [83]. Because of the high cost of feedstock, biofuels is more costly than conventional pretroleum fuels. Economic analysis show that the demand for biofuels can result in high food prices; which can lead to higher rate of malnutrition in the developing countries [83]. Nevertheless, this theory is not valid for biofuels from food waste.

## 4. Future prospects and policies

Clearing lands rich with carbon habitats for growing biofuels crops will increase carbon debt [29]. Thus, biofuels obtained from crops which are grown in land meant for carbon rich habitats is not sustainable. Moreover, cost of feedstocks accounts for 80–90% cost of liquid biofuels [21]. In general, edible feedstocks are traded in food markets and its value is completely affected by food and biofuel demands. Alternatively, waste non-edible substances which are discared viz. waste cooking oil and food waste can be recycled as biofuels [84].

The future policy should be focussed on using this no-value resource to produce high value products. For instance, sustainable valorization technologies should be developed to produce biofuels such as biodiesel, bioethanol and biooil. Such efforts are advantageous for many resons such as (i) it will make the countries energy self-sufficient, (ii) it will contribute toward a stronger local economy, (iii) solve the pollution and space problem in metropolis, and (iv) help to build a sustainable biobased economy. In future, solid acid catalysts can be used as green catalysts for biodiesel production from food waste [85].

High carbohydrate, protein and lipid content make food wastes very good resource for biofuels and chemicals production. Apart from biofuels the food wastes can be converted to different value added products (Fig. 6). Since food wastes contain low lignin in many cases very little or no pretreatment required for the conversion to biofuel compared to agricultural and forest residues. Along this line, food waste can be hydrolzyed by using proteases to form hydrolysate and crude lipid rich biomass [38,39]. The hydrolysate mainly contain carbohydrates, amino acids, phosphates and other nutrients. Thus, the hydrolysate can be used as a nutrient medium for the growth of microorganisms [38,39] (Fig. 6). Different biofuels producing microorganisms can be grown on food hydrolysate. For instance, microalgae can be grown on food hydrolysate. The microalgae is rich in lipid biomass. Lipid from these microalgae can be extracted. These lipids contain polyunsaturated fatty acids (PUFA). Furthermore, lipids extracted from microalgae can be converted to biodiesel, surfactants and epoxides [86] (Fig. 6). After production of biodiesel the obtained glycerol can be subjected to pyrolysis to form biooil (Fig. 6). Furthermore, the obtained gycerol can be converted to structured glycerides via lipase catalysis (Fig. 6). The food hydrolysate rich in carbohydrate can be used for the production of bioethanol (Fig. 6). Advantages and disadvantages of different biofuel production processes from food waste are evaluated (Table 2).

RWL Water Group-an international company is known to install waste-to-energy systems for the efficient conversion of food waste from slaughterhouses, breweries, dairy farms and coffee shops [87]. Furthermore, these systems can be installed in homes for power generation if infrastructure is in place to sort, collect and process the food wastes. Enerkem Alberta Biofuels LP is building a biofuel plant at Edmonton, Canada. Using the available technology Enerkem aims to convert 100,000 t of municipal waste into 38 million liters of biofuels and chemicals annually [88]. "Greenergy" – a company located in Britain is converting waste oils to biodiesel [89]. Along this line, a pilot scale production of ethanol from food waste using *S. cerevisiae* H058 is reported by Yan et al. [76].

Techno-economic evaluation of "food waste to energy" processes needs to be performed to know the commercial viability. Food waste composition is largly dependent on different factors such as (i) place of food waste generation, (ii) timing of collection

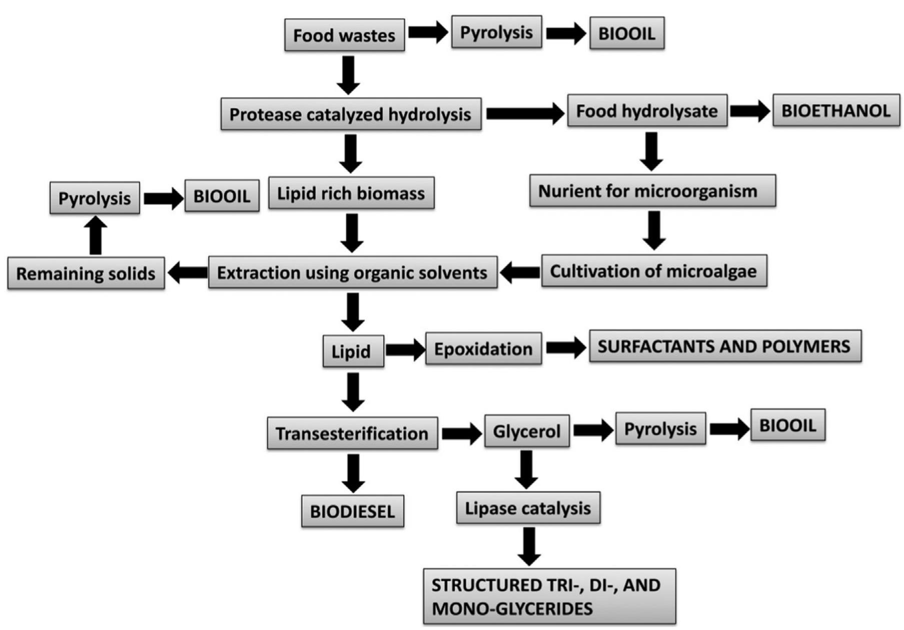



**Fig. 6.** A schematic representation of possible routes for the preparation of different biofuels and value added products from food wastes.

**Table 2**
Evaluation of processes for conversion of food waste to liquid biofuels [15,16].

| | Advantages | Disadvantages | Comments |
|---|---|---|---|
| Conversion to liquid biofuels | • Sustainable utilization of food wastes.<br>• An alternative to fossil fuel.<br>• Energy security and less dependent on politically unstable middle east countries.<br>• Space problems in metropolitan areas can be circumvanted.<br>• Small biofuel plants can be operated near food parks. | • High operational cost.<br>• No cost-effective methods are available so far; especially for mixed food waste.<br>• Advanced and economical valorization methods need to be developed to deal with diverse nature of food wastes.<br>• Most of the ongoing research are in preliminary stages. | • Most of the methods are chemical and biochemical processes.<br>• Technology for mixed food waste valorization is rather complicated.<br>• Catalytic cascade reactions can be tried as an alternative technology.<br>• For extraction of lipids green solvents such as $scCO_2$ can be explored. |

of food waste, and (iii) food habits of people. Therefore, food wastes are rather complex and diverse in nature. Well designed valorization strategies can be devised to trap these food waste and can be converted to high value products [90]. Sucessful utilization of food waste is also dependent on the development of new and cost-effective technologies that can be used for waste valorization. For instance, collaboration between different research areas such as chemo-catalysis, bio-catalysis, biotechnology, downstrem processing, and environmental engineering are required for developing cutting edge food waste valorization technologies.

Food waste recycling and its utilization as a resource is hampered by fuggy and outdated regulations, which is supported by low level of social awarness. Many important intitiatives and campaigns are needed by civil society groups, non-government organizations, food industries and government to bring awarness among the people about the value of food waste and aginst the traditional perception that waste needs to thrown away. Furthermore, goverment organization should formulate policies to promote enterpreanues and industrialists for the utilization of food wastes. A fixed budget needs to be allocated in each financial year to build and manage food waste recycling facilities. Generally, taxes have biggest impact on the cost of biofuel and duty reductions are required to make biofuel cheaper. Such policies and initiatives will help in building a sustainable society.

## 5. Challenges and remarks

Food waste is a no-value resource that can be used for liquid biofuel production. Nevertheless, there are many challenges that needs proper attention. Since, this is an emerging research area a proper understanding and discusssion on different points pertaining to food wastes will help to overcome the limitations.

### 5.1. Unorganized sector

Collection of food waste is still a challenge as it is an unorganized sector. General perception about food waste is that it should be thrown away; this mindset is a big challenge for its collection. Social campaign is needed to highlight the importance of food waste. Urban planning and housing departments along with food industries should devise a proper plan for the smooth collection of food waste. Enthusiastic volunteers should be encouraged to turn up everyday to transport the food wastes to community collection facilities. Such efforts will make the food waste collection process much faster and easier.

### 5.2. Separation of food waste

In many places food waste is generally mixed with other solid municipal wastes. Proper sepration and sorting methods of food wastes from non-biological wastes are required for its further processing and utilization. Since, food waste is diverse and complex the sepration strategy might change from place to place depending upon the types of food waste.

### 5.3. Non-renewable

Food waste is non-renewable. Better management of food production and its utilization will minimize the generation of food waste. Starting large industries to recycle the food waste will need continous suppy of huge qunatities of food waste. In this context, sustaining a big industry based on food waste is not pragmatic. Therefore, small and medium biofuel production plants can be attached to big restaurants and food parks. This will also reduce the transportation cost of the food wastes.

### 5.4. Non-standard resource

Composition of food waste is largely dependent on the place, eating habits and eating timings. Therefore, before using it as a resource for the preparation of biofuels its chemical composition and water content needs to be determined. Unlike, standard feedstocks such as plant oils, corn, and lignocellulosic materials the food waste is rather complex. Therefore, a proper characterization method should be in place for the complete chemical chracterization of different types of food wastes.

### 5.5. Downstream processing

Food waste contain lipid, carbohydrate, amino acids, phosphates, vitamins and other nutrients. Individual separation and purification of lipid, carbohydrate, and carbon containing materials from food waste will be costly. This also require volatile organic solvents (VOCs) which are harmful for health and environment. Alternatively, simultaneous biodiesel, bioethanol and bioil production methods should be developed in a single reaction system without any purification and isolation of lipid, carbohydrates and other components. This will make the whole process much simpler and cost-effective.

## 6. Conclusions

Food waste is a no-value and non-edible resource. Thus, it can be used to develop cost-effective process for the production of biofuels. Academic and industrial research are currently focused on developing innovative food valorization strategies for the conversion of food waste into biofuels and value added products. The future work should focus on the feasibility of utilizing food waste into biofuels in large scale by cost-effective chemical and biochemical methods.

## References

[1] Demirbas A. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energy Convers Manag 2008;49:2106–16.
[2] Pimentel D, Patzek TW. Ethanol production using corn, switch grass, and wood; biodiesel production using soybean and sunflower. Nat Resour Res 2005;14:65–76.
[3] Demirbas A. Importance of biodiesel as transportation fuel. Energy Policy 2007;35:4661–70.
[4] Demirbas A. Progress and recent trends in biodiesel fuels. Energy Convers Manag 2009;50:1–34.
[5] Borugadda VB, Goud VV. Biodiesel production from renewable feedstocks: status and opportunities. Renew Sustain Energy Rev 2012;16(7):4763–84.
[6] Fan X, Burton R. Recent development of biodiesel feedstocks and the applications of glycerol: a review. Open Fuel Energy Sci J 2009;2:100–9.
[7] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddin IA, Fayaz H. Non-edible-vegetable oils: A critical evaluation of oil etraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sustain Energy Rev 2013;18:211–45.
[8] Ma F, Hanna MA. Biodiesel production – a review. Bioresour Technol 1999;70:1–15.
[9] Machetti JM, Miguel VU, Errazu AF. Techno-economic study of different alternatives for biodiesel production. Fuel Process Technol 2008;89:740–8.
[10] Leung DYC, Wu X, Leung MKH. A review on biodiesel production using catalyzed transesterification. Appl Energy 2010;87:1083–95.
[11] Gustafsson U, Wills W, Draper A. Food and public health: contemporary issues and future directions. Critic. Public Health 2011;21(4):385–93.
[12] Melikoglu M, CSK Lin, Webb C. Analysing global food waste problem: pinpointing the facts and estimating the energy content. Cent Eur J Eng 2013; 3(2):157–64.
[13] OECD. Municipal waste generation. In: OECD, editor. Municipal waste generation. Tokyo: OECD Publishing; 2007.
[14] Kiran EU, Trzcinski AP, Ng WJ, Liu Y. Bioconversion of food waste to energy: a review. Fuel 2014;134:389–99.
[15] A food waste & yard waste plan for Hong Kong. 〈http://www.enb.gov.hk/en/files/FoodWastePolicyEng.pdf〉; 2014–2022 [accessed 11.02.15].

[16] Monitoring of solid waste in Hong Kong. ⟨https://www.wastereduction.gov.hk/en/assistancewizard/waste_red_sat.htm⟩; 2015 [accessed 11.02.15].

[17] Garcia J. Food waste recycled as biofuel. ⟨http://large.stanford.edu/courses/2011/ph240/garcia1/⟩; 2014 [accessed 08.02.14].

[18] Karmee SK, Lin CSK. Valorisation of food waste to biofuel: current trends and technological challenges. Sustain Chem Process 2014;2:22. http://dx.doi.org/10.1186/s40508-014-0022-1.

[19] Karmee SK, Lin CSK. Lipids from food waste as feedstock for biodiesel production: Case Hong Kong. Lipid Technol 2014;26:206–9.

[20] Pham TPT, Kaushik R, Parshetti GK, Russell M, Balasubramanian R. Food-waste-to-energy conversion technologies: current status and future directions. Waste Manag 2014.

[21] Chhetri AB, Watts KC, Islam MR. Waste cooking oil as an alternate feedstock for biodiesel production. Energies 2008;1:3–18.

[22] Gnanaprakasam A, Sivakumar VM, Surendhar A, Thirumarimurugan M, Kannadasan T. Recent strategy of biodiesel production fr om waste cooking oil and process influencing parameters: a review. J Energy 2013:1–10. http://dx.doi.org/10.1155/2013/926392.

[23] Yaakob Z, Mohammad M, Alherbawi M, Alam Z, Sopian K. Overview of the production of biodiesel from waste cooking oil. Renew Sustain Energy Rev 2013;18:184–93.

[24] Khan TMY, Atabani AE, Badruddin IA, Badarudin A, Khayoon MS, Triwahyono S. Recent scenatio and technologies to utilize non-edible oils for biodiesel production. Renew Sustain Energy Rev 2014;37:840–51.

[25] Karmee SK, Chadha A. Preparation of biodiesel from crude oil of Pongamia Pinnata. Bioresour Technol 2005;96:1425–9.

[26] Karmee SK, Chandna D, Ravi R, Chadha A. Kinetics of base-catalyzed transesterification of triglycerides from Pongamia oil. J Am Oil Chem Soc 2006; 83(10):873–7.

[27] Karmee SK, Mahesh P, Ravi R, Chadha A. Kinetic study of the base-catalyzed transesterification of monoglycerides from Pongamia oil. J Am Oil Chem Soc 2004;81(5):425–30.

[28] Sun Y, Cheng J. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresour Technol 2002;83:1–11.

[29] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land claering and the biofuel carbon debt. Science 2008;319:1235–8.

[30] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R. Beneficial biofuels – the food, energy, and environment trilemma. Science 2009;325:270–1.

[31] Mathews JA. Is growing biofuel crops a crime against humanity. Biofuels Bioprod Biorefin 2008;2(2):97–9.

[32] Chen Y, Xiao B, Chang J, Fu X, Lv P, Wang X. Synthesis of biodiesel from waste cooking oil using immobilised lipase in fixed bed reactor. Energy Convers Manag 2009;50:668–73.

[33] Enweremadu CC, Mbarawa MM. Technical aspects if production and analysis of biodiesel from used cooking oil – a review. Renew Sustain Energy Rev 2009;13:2205–24.

[34] Luque R, Clark JH. Valorisation of food residues: waste to wealth using green chemical technologies. Sustain Chem Process 2013;1:10.

[35] Heo HS, Kim SG, Jeong K-E, Jeon J-K, Park SH, Kim JM, Kim S-S, Park Y-K. Catalytic upgrading of oil fractions separated from food waste leachate. Bioresour Technol 2011;102:3952–7.

[36] Ahmed II, Gupta AK. Pyrolysis and gasification of food waste: syngas characteristics and char gasification kinetics. Appl Energy 2010;87(1):101–8.

[37] From waste to liquid energy-bio oil holding. ⟨http://www.bio-oil-holding.eu/EN/bio-oil-english.pdf⟩; 2015 [accessed 14.02.15].

[38] Pleissner D, Kwan TH, CSK Lin. Fungal hydrolysis in submerged fermentation for food waste treatment and fermentation feedstock preparation. Bioresour Technol 2014;137:139–46.

[39] Pleissner D, Lam WC, Sun Z, CSK Lin. Food waste as nutrient source in heterotrophic microalgae cultivation. Bioresour Technol 2014;137:139–46.

[40] Karmee SK, Greiner L, Krayanov A, Müller TE, Niemeijer B, Leitner W. Nanoparticle catalysed oxidation of sulfides to sulfones by in situ generated H2O2 in supercritical carbon dioxide/water biphasic medium. Chem Commun 2010;46:6705–7.

[41] Karmee SK, Roosen C, Kohlmann C, Lütz S, Greiner L, Leitner W. Chemoenzymatic cascade oxidation in supercritical carbon dioxide/water biphasic media. Green Chem 2009;11:1052–5.

[42] Yang X, Lee SJ, Yoo HY, Choi HS, Park C, Kim SW. Biorefinery of instant noodle waste to biofuels. Bioresour Technol 2014;159:17–23.

[43] Yang X, Lee SJ, Yooo HY, Shin HY, Thapa LP, Park C, Kim SW. Production of bioetanol and biodiesel using instant noodle waste. Bioprocess Biosyst Eng 2014;37:1627–35.

[44] Karmee SK, Niemeijer B, Casiraghi L, Mlambo B, Lapkin A, Greiner L. Facile biocatalytic synthesis of a macrocyclic lactone in sub- and supercritical solvents. Biocatal Biotrans 2014;32(2):125–31.

[45] Karmee SK. Lipase catalyzed synthesis of ester-based surfactants from biomass derivatives. Biofuels Bioprod Biorefin 2008;2(2):144–54.

[46] Karmee SK. Biocatalytic synthesis of ascorbyl esters and their biotechnological applications. Appl Microbiol Biotechnol 2009;81(6):1013–22.

[47] Parawira W. Biotechnological production of biodiesel fuel using biocatalysed transesterification: A review. Crit Rev Biotechnol 2009;29(2):82–93.

[48] Fukuda H, Hama S, Tamalampudi S, Noda H. Whole-cell biocatalysts for biodiesel fuel production. Trends Biotechnol 2008;26(12):668–73.

[49] Robles-Medina A, González-Moreno PA, Esteban-Cerdán L, Molina-Grima E. Biocatalysis: towards ever greener biodiesel production. Biotechnol Adv 2009;27(4):398–408.

[50] Ranganathan SV, Narasimhan SL, Muthukumar K. An overview of enzymatic production of biodiesel. Bioresour Technol 2008;99:3975–81.

[51] Bana K, Kaieda M, Matsumoto T, Kondo A, Fukuda H. Whole cell biocatalyst for biodiesel fuel production utilizing Rhizopus oryzae cells immobilized within biomass support particles. Biochem Eng J 2001;8:39–43.

[52] Karmee SK, Linardi D, Lee J, CSK Lin. Conversion of lipid from food waste to biodiesel. Waste Manag 2015;41:169–73. http://dx.doi.org/10.1016/j.wasman.2015.03.025.

[53] Berg C. World bioethanol production, the distillery and bioethanol network. ⟨http://www.distill.com/worldethanolproduction.htm⟩; 2001.

[54] Taherzadeh MJ, Karimi K. Acid based hydrolysis processes for ethanol from lignocellulosic materials: a review. Bioresources 2007;2(3):472–99.

[55] Kim S, Dale BE. Global potential bioethanol production from wasted crops and crop residues. Biomass Bioenergy 2004;26:361–75.

[56] Arapoglou D, Varzakas T, Vlyssides A, Israilides C. Ethanol production from potato peel waste (PPW). Waste Manag 2010;30:1898–902.

[57] Akpan UG, Alhakim AA, UJJ Ijah. Production of ethanol fuel from organic and food wastes. Leonardo Electron J Pract Technol 2008;13:1–11.

[58] Cekmecelioglu D, Uncu ON. Kinetic modeling of enzymatic hydrolysis of pretreated kitchen wastes for enhancing bioethanol production. Waste Manag 2013;33(3):735–9.

[59] Hong YS, Yoon HH. Ethanol production from food residues. Biomass Bioenergy 2011;35(7):3271–5.

[60] Kawa-Rygielska J, Pietrzak W, Czubaszek A. Characterization of fermentation of waste wheat-rye bread mashes with the addition of complex enzymatic preparations. Biomass Bioenergy 2012;44:17–22.

[61] Kim JH, Lee JC, Pak D. Feasibility of producing ethanol from food waste. Waste Manag 2011;31:2121–5.

[62] Kim JK, Oh BR, Shin H-J, Eom C-Y, Kim SW. Statistical optimization of enzymatic saccharification and ethanol fermentation using food waste. Process Biochem 2008;43:1308–12.

[63] Kumar JV, Shahbazi A, Mathew R. Bioconversion of solid food wastes to ethanol. Analyst 1998;123(3):497–502.

[64] Koike Y, An M-Z, Tang Y-Q, Syo T, Osaka N, Morimura S, Kida K. Production of fuel ethanol and methane from garbage by high efficiency two-stage fermentation process. J Biosci Bioeng 2009;108(6):508–12.

[65] Li H, Yang L, Kim Y-J, Kim S-J. Continuous ethanol production by the synchronous saccharification and fermentation using food wastes. Korean J Chem Eng 2011;28(4):1085–9.

[66] Matsakas L, Kekos D, Loizidou M, Christakopoulos P. Utilization of household food waste for the production of ethanol at high dry material content. Biotechnol Biofuels 2014;7:4. http://dx.doi.org/10.1186/1754-6834-7-4.

[67] Ma KD, Wakisaka M, Kiuchi T, Praneetrattananon S, Morimura S, Kida K, Shirai Y. Repeated-batch ethanol fermentation of kitchen refuse by acid tolerant flocculating yeast under the non-sterilized condition. Jpn J Food Eng 2007; 8(4):275–9.

[68] Ma H, Wang Q, Qian D, Gong L, Zhang W. The utilization of acid-tolerant bacteria on ethanol production from kitchen garbage. Renew Energ 2009; 34(6):1466–70.

[69] Oberoi HS, Vadlani PV, Nanjundaswamy A, Bansal S, Singh S, Kaur S, Babbar N. Enhanced ethanol production from Kinnow mandarin (*Citrus reticulata*) waste via a statistically optimized simultaneous saccharification and fermentation process. Bioresour Technol 2011;102(2):1593–601.

[70] Oberoi HS, Vadlani PV, Saida L, Bansal S, Hughes JD. Ethanol production from banana peels using statistically optimized simultaneous saccharification and fermentation process. Waste Manag 2011;31(7):1576–84.

[71] Sharma N, Kalra KL, Oberoi HS, Bansal S. Optimization of fermentation parameters for production of ethanol from kinnow waste and banana peels by simultaneous saccharification and fermentation. Ind J Microbiol 2007;47(4):310–6.

[72] Sulaiman A, Othman N, Baharuddin AS, Mokhtar MN, Tabatabaei M. Enhancing the halal food industry by utilizing food wastes to produce value-added bioproducts. Proced Soc Behav Sci 2014;121:35–43.

[73] Tang YQ, Koike Y, Liu K, An M-Z, Morimura S, Wu X-L, Kida K. Ethanol production from kitchen waste using the flocculating yeast Saccharomyces cerevisiae strain KF-7. Biomass Bioenergy 2008;32(11):1037–45.

[74] Wang Q, Ma H, Xu W, Gong L, Zhang W, Zou D. Ethanol production from kitchen garbage using response surface methodology. Biochem Eng J 2008; 39(3):604–10.

[75] Yan S, Li J, Chen X, Wu J, Wang P, Ye J, Yao J. Enzymatical hydrolysis of food waste and ethanol production from the hydrolysate. Renew Energy 2011;36:1259–65.

[76] Yan S, Chen X, Wu J, Wang P. Pilot scale production of fuel ethanol from concentrated food waste hydrolysates using Saccharomyces cerevisiae H058. Bioprocess Biosyst Eng 2013;36:937–46.

[77] Yan S, Wang P, Zhai Z, Ya J. Fuel ethanol production from concentrated food waste hydrolysates in immobilized cell reactors by Saccharomyces cerevisiae H058. J Chem Technol Biotechnol 2011;86(5):731–8.

[78] Bello RH, Linzmeyer P, Franco CMB, Souza O, Sellin N, Medeiros SHW, Marangoni C. Pervaporation of ethanol produced from banana waste. Waste Manag 2014;34:1501–9.

[79] Kaushik R, Parshetti GK, Liu Z, Balasubramanian R. Enzyme-assisted hydrothermal treatment of food waste for co-production of hydrochar and bio-oil. Bioresour Technol 2014;168:267–74.

[80] Hertel T, Golub A, Jones A, O'Hare M, Plevin R, Kammen D. Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. BioScience 2010;60:223–31.

[81] Huang H, Khanna M, Onal H, Chen X. Stacking low carbon policies on the renewable fuels standard: economic and greenhouse gas implications. Energy Policy 2013;56:5–15.
[82] Economics of Biofuels. 〈http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/Biofuels.html〉; 2015 [accessed 25.05.15].
[83] Skarlis S, Kondili E, Kaldellis JK. Small-scale biodiesel production economics: a case study focus on crete Island. J Clean Prod 2012;20:20–6.
[84] Gude VG, Grant GE, Patil PD, Deng S. Biodiesel production from low cost and renewable feedstock. Cent Eur J Eng 2013;3:595–605. http://dx.doi.org/10.2478/s13531-013-0102-0.
[85] Kiss AA, Dimian AC, Rothenberg G. Solid acid catalysts for biodiesel production- towards sustainable energy. Adv Synth Catal 2006;348:75–81.
[86] Pleissner D, Lau KY, Zhang C, Lin CSK. Plasticizer and surfactant formation from food-waste- and algal biomass-derived lipids; 2014. doi: 10.1002/cssc.201402888.
[87] Wasted energy: converting discarded food into biofuels promises global energy boon. 〈http://www.scientificamerican.com/article/food-waste-to-energy/〉; 2015 [accessed 25.05.15].
[88] Waste-to-biofuels and chemicals facility. 〈http://www.edmonton.ca/programs_services/garbage_waste/biofuels-facility.aspx〉; 2015 [accessed 25.05.15].
[89] Biofuels from wastes. 〈http://www.greenergy.com/Operations/biofuels_wastes.html〉; 2015 [accessed 25.05.15].
[90] Yang X, Choi HS, Park C, Kim SW. Current states and prospects of organic waste utilization for biorefineries. Renew Sustain Energy Rev 2015;49:335–49.

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# Technology, complexity and change in agricultural production systems

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## Abstract

Technological advances have contributed to impressive yield gains and have greatly altered US agriculture. Selective breeding and directed molecular techniques address biological shortcomings of plants and animals and overcome environmental limitations. Improvements in mechanization, particularly of power sources and harvest equipment, reduce labor requirements and increase productivity and worker safety. Conservation systems, often designed to overcome problems introduced from other technologies, reduce negative impacts on soil and water and improve the environmental sustainability of production systems. Advances in information systems, largely developed in other disciplines and adapted to agriculture, are only beginning to impact US production practices. This paper is the fourth in the series of manuscripts exploring drivers of US agricultural systems. While development of technology is still largely driven by a need to address a problem, adoption is closely linked with other drivers of agricultural systems, most notably social, political and economic. Here, we explore the processes of innovation and adoption of technologies and how they have shaped agriculture. Technologies have increased yield and net output, and have also resulted in decreased control by producers, increased intensification, specialization and complexity of production, greater dependence on non-renewable resources, increased production inputs and hence decreased return, and an enhanced reliance on future technology. Future technologies will need to address emerging issues in land use, decline in work force and societal support of farming, global competition, changing social values in both taste and convenience of food, and increasing concerns for food safety and the environment. The challenge for farmers and researchers is to address these issues and develop technologies that balance the needs of producers with the expectations of society and create economically and environmentally sustainable production systems.

**Key words:** technology, sustainability, technological drivers, genetic improvements, mechanization, conservation systems, information systems

## Introduction

The 20th century's unprecedented advances in the application of biological science and engineering to agriculture have revolutionized farming. Technologies are implicitly functional, benefiting society by solving a problem or circumventing a functional constraint. Agricultural technologies include both engineering and biological inventions and discoveries, such as modifications to machinery, the physical environment or biological components of a system. Knowledge systems, such as decision support tools and management systems, are examples of cultural technologies.

The intensification of agriculture over the past 50 years has resulted in impressive yield improvements[1]. In the US, yields have risen steadily, with corn yields roughly tripling and wheat and soybean yields approximately doubling over the past half-century (Fig. 1a)[2]. Similar gains in animal production have increased egg production in chickens by 18% in the past 16 years, milk production

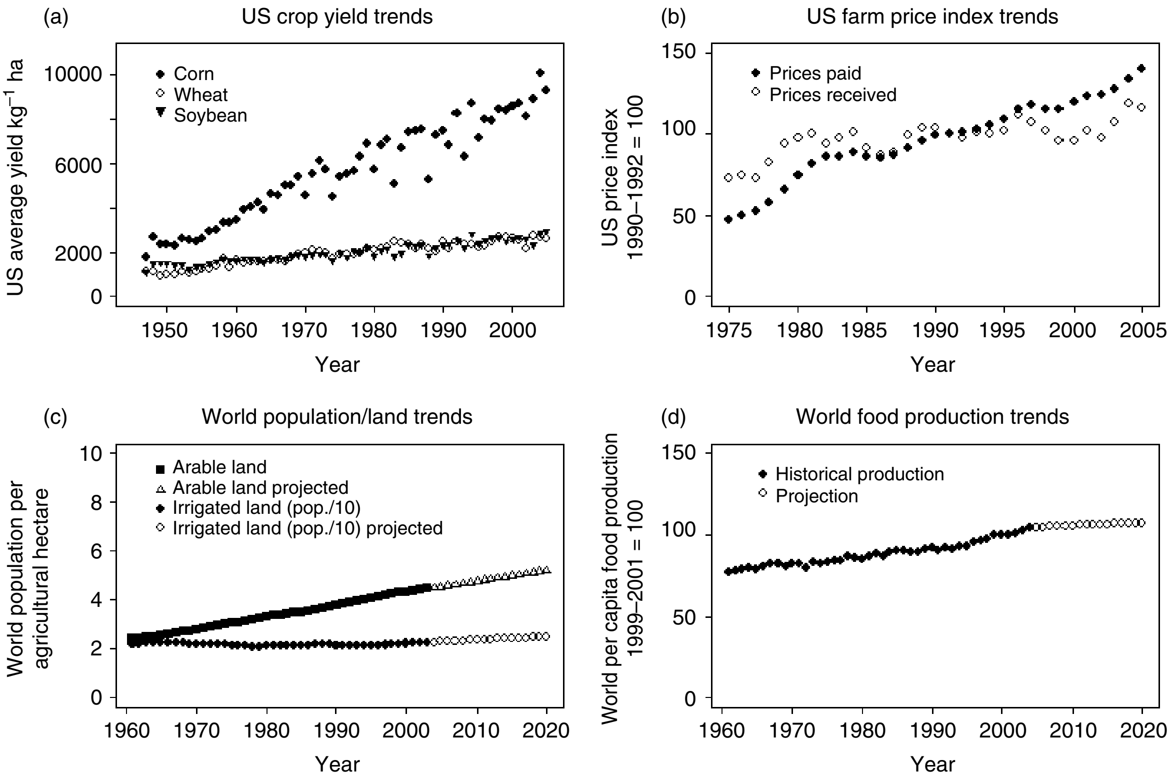


**Figure 1.** Historical and projected trends in agriculture.

in cows by 28% in the past 10 years, and average live broiler chicken weight by 155% in the past 80 years[3].

While addressing concerns of a growing world-wide population, these impressive yield gains have come at a cost to natural resources[4] and the farming community[5]. Capital intensive technologies required to realize these gains can favor agribusiness over family farms[5]. The continued development of new technologies, at times needed to address issues introduced from adoption of previous technologies, puts farmers on a technology treadmill[6] that limits their flexibility in making management decisions. Globalization has increased competition and generated new problems and opportunities. Current technologies have opened a proverbial Pandora's Box of opportunities, risks and hope for future developments.

In this manuscript, we explore how the technological revolution has altered American agriculture and how it is likely to contribute to changes in future production practices. We examine the traditional development and adoption cycle, and explore new models of innovation delivery that are changing the process of technological advancement. Our premise is that as the world population and agricultural productivity move towards sustainability, agricultural problems will become more difficult to solve with strategies focused solely on increasing yield potential. Agricultural productivity will need to shift from a simplistic focus on yield per hectare to incorporate a broader, interdependent set of constraints including all inputs to the production cycle: natural resources, financial and human resources[4]. We explore five fundamental ways that technology has impacted farming: (1) increased intensification of production, (2) increased reliance on natural resources, particularly soil and water, and non-renewable resources, primarily fossil fuels, (3) increased production inputs and dependence on future technology, leading to a technology treadmill that limits choices, (4) increased complexity of the farming system, and (5) decreased control by producers. These trends in agriculture have led to declining support for agricultural production as fewer people are directly involved with farming; increased degradation of natural resources through contamination of soil, water and atmosphere; depletion of natural resources, particularly water and fossil fuels; and decreasing profit margins. To address the interconnected constraints facing American agriculture and ensure future advances in agricultural productivity, multidisciplinary problem solving approaches will become increasingly important.

## *Processes of innovation and adoption*

The problems and needs of the production community drive the interdependent processes of development and adoption to bring an innovation into use. Rather than a linear event, these two processes occur in a continuous spiral, with continued adaptation and modification of a technology furthering the advancement and continuing the cycle[7].

The traditional processes of technology development and adoption have been described as a linear or 'Push' system[8,9] in which the problem is identified and technology developed for delivery to the end user. This method works well during crisis conditions, such as invasive pests or diseases (e.g. Karnal–Bundt and avian flu), or for problems requiring a high input of technical expertise or capital, such as development of genetic modification techniques.

Emerging models of development and adoption rely on closer interaction between technical developers and non-technical end-users. In a ‘learning selection’ model, developers interact closely with a self-selected group of interested end-users, and use their knowledge base to refine the initial design concept to the needs of the user group[8]. As the development–adoption process continues, the initial user group becomes invested in the technology and plays a key role in the dissemination of the information and adoption of the technology by a larger user group. This model works well in the development and delivery of mechanized agricultural technology, such as harvesting equipment[8]. In the ‘Pull’ model[9], a platform for information exchange is established that expands the base of knowledge available to the developers and end-users by bringing together large groups of diverse individuals to solve or influence a problem. Complexity and chaos are seen as opportunities for expansion of ideas rather than as negative factors that need to be controlled. This emerging model is operating in media, global process networks and education. The ‘Pull’ model holds particular promise for the large, complex problems, ranging from social to technical, that face today’s agriculture. Expansion of the knowledge base, through increased participation of people from a diversity of disciplines, has the potential to enhance the creativity applied to solve emerging agricultural production issues.

The process of adoption is driven by interactions between a broad range of external and internal factors, such as political readiness, social and political pressure and monetary constraints[10]. Farmers have a desire for increased profitability and greater lifestyle security[5,11]. Competition from global markets has also facilitated adoption of new technologies as farmers recognize the need to remain competitive[12]. Innovations that reduce production risk and are relatively simple to use are most successfully adopted[13]. In addition, farmers who have ready access to an expert are much more likely to implement new technologies[14].

### *Problems driving innovation*

Fundamental limitations to agricultural production arise from edaphic, abiotic and biotic constraints of the natural environment. Water has a particular global significance[15], and limits production in many areas due to quantity and quality constraints, as well as pumping costs. The biological capacity of crops and animals also limits yield. Natural resource limitations are critical to current and future production, and future impacts of global warming and climate change are of increasing concern to farmers. Additionally, the availability and expense of fossil fuels has become a concern as they are needed both as fuel for tractors and for fertilizer production.

Social and political pressures alter the expectations from agriculture[5]. Changes in the social conscience moved society towards the industrial model of success based on production output. Simultaneously, growing awareness of inequities in food availability encouraged aggressive production goals to increase the worldwide per capita caloric uptake[16]. To increase production levels with a declining pool of laborers for farm work, farmers needed to do more work with fewer people[17]. Legislation impacts major decisions through set-aside programs or price supports and the adoption of specific technologies directly, such as the 1996 Food Quality Protection Act[18]. The current discussion of environmental credits versus commodity payments will further impact farmers’ decisions as to which production systems to implement[5,19]. Human resource limitations in management expertise and time further hinder productive capacity, requiring improved marketing and management skills to remain competitive.

## Technological Advances

### *Genetic improvements*

Advances in our understanding of reproductive biology and the mechanisms of inheritance enhanced our ability to make directed changes in crop and animal traits, improve yield, address environmental limitations, and overcome a host of production constraints. Genetic manipulation by selective breeding or direct molecular techniques is an established method for improving productive capacity and the regional usefulness of crops. Other technologies, such as weed and insect control and resistance to or control of diseases, increase productivity by preventing indirect competitive losses.

Hybrid maize was one of the 20th century’s major scientific innovations contributing to yield improvements, and is widely cited as one of the most rapidly adopted agricultural technologies in the 20th century[20,21]. In addition to the yield advantages with hybrid crops, the greater crop uniformity increased the ease of management. Prior to the introduction of hybrids, a field of maize contained a mixture of unique genotypes varying in economically important traits such as ear height, maturity and grain characteristics. This variation made mechanization of production difficult, especially harvest. Mechanized harvesting of corn coincided with the adoption of hybrids[22]. Both improvements in yield and management hastened the adoption of hybrid technologies.

Though greater uniformity in the timing of plant developmental events may be desirable for timing of agricultural inputs and harvest, this uniformity renders the crops more susceptible to catastrophic losses from insects and pathogens. By compromising the seeds’ natural defensive abilities by selecting for more desirable traits, producers must increasingly rely on chemical control methods and increased management for some of the functionality that the crop once provided for itself. Extensive implementation of monoculture production has increased reliance on technologies such as chemical control methods and reduced crop diversity.

Hybrids have also instrumented a substantial paradigm shift in how society views genomic property rights, and played a role in the evolution of the seed industry. With hybrid technology, farmers must buy the seed each year rather than saving seed from the previous harvest. Competitors cannot sell a company's hybrids unless they obtain the rights. Development of hybrids and subsequent genetic modifications have removed natural genetic material from public ownership and placed it in the hands of a few companies[23]. As development and adoption of genetically altered materials increases, the production system becomes more complex. Moreover, producers increasingly lose control of their production decisions, as the management technology is genetically hard-wired in the seed[23].

The social response to genetic technologies is most apparent in the current debate over genetically modified organisms (GMOs)[24,25]. While opponents of the technology accuse agribusiness of profiteering at the expense of risks to public health, the purported harms of GMOs are often ascribed to political posturing and anti-science[26] by supporters of the technology. Regardless of one's support[25] or contempt[27] for the technology, it is obvious that it has had, and will continue to have, substantial social impacts[28].

As with plants, the natural genetic variations in animals have been used to selectively improve animal stocks. Until the mid-20th century, the formation of most modern breeds of livestock was defined by the breeders themselves and selection was strongly influenced by livestock competitions. Development of artificial insemination (AI) dramatically increased productivity, especially of dairy cows[29]. Combined academic and industrial research addressed a major constraint on genetic improvement through development of semen extenders, a method of freezing semen, and a convenient method of safely transporting frozen semen. Improved quantitation of genetic lineage has allowed managers and advisors to evaluate and benchmark their specific management strategies. Widespread dissemination of extended and frozen semen has resulted in international commerce of tens of millions of semen doses[30].

Formation of farmer-owned AI cooperatives and long- and short-term experiments conducted on cooperator farms were keys to the successful adoption of AI[29]. While these initial cooperatives were formed between producers, advances in AI technologies led to the consolidation of AI organizations and increased investment by privately held companies[31].

Modern gene manipulation tools have expanded our capacity for improvements and are used in animal and aquaculture systems to identify superior traits, enhance breeding programs, facilitate disease resistance and establish, meet and verify standards. Molecular genetics can be used to improve the population through identification of genes and genetic markers associated with a desired trait, such as disease resistance, improved growth rate or meat quality. Biotechnology in animal systems can be used to do the same things currently done through traditional breeding, but more quickly, more accurately, and (or) with a different price structure, thereby changing competitive advantages among individuals, companies and countries.

In the dairy industry, improved genetic evaluations for milk production led to rapid increases in milk production and a subsequent decline in the number of cows needed to sustain production levels. Mechanization and other improvements in dairy production intensified the consolidation of dairy farms. The reduction in nationwide herd size and consolidation of dairy farms has led to a reduced genetic diversity and increased inbreeding, which may be contributing to the recently observed reduction in fertility[31]. While genetic improvements of animals have increased performance and yield, as with crops, they have been associated with (a) a loss of farms through consolidation, (b) a decline in farmer control of the production process, and (c) an increased complexity of the farming system.

### Mechanization

In the US, social pressures have driven the evolution of agriculture to deliver abundant, inexpensive, readily available foods year round. The changing social conscience introduced with industrialization shifted the social expectations away from farming as a way of life towards efficiency and production output[32]. Technological advances developed during and immediately after World War II increased mechanization and introduced chemicals to manage soil fertility and pests. Changes in commodity supports[10] and increased social pressure to feed the world further directed production towards large-scale monoculture agriculture[16]. While advances in biological and engineering technologies made large-scale monoculture production possible, changes in the social conscience made it desirable.

To address the social demands for food and expand production and improve yields, farmers needed easier, faster, less labor-intensive and more efficient means of managing crops. Mechanization of US agriculture during the 19th and 20th centuries began with the introduction of the tractor which removed much of the backbreaking toil, increased the speed, efficiency and amount of work that could be accomplished and improved worker safety[33]. Throughout the industrial revolution, innovations in farm machinery have dramatically decreased labor demands and improved the efficiency and effectiveness of field operations. The fraction of the population involved in agricultural production continues to decrease. Improved harvest, storage and transportation technologies have all contributed to greater efficiency and allowed feeding a growing population without substantial increases in land devoted to production agriculture.

A major benefit of mechanization is greater efficiency during the harvest operation which minimizes yield and quality loss due to extended exposure to bad weather. Cotton (*Gossypium* sps., L.) has played a significant role in clothing humanity for centuries. Its technological advancement is often a leading sector indicating the level of industrialization of a country. Development of mechanical cotton harvesters substantially impacted the social and economic development of the cotton-growing regions of the US[34]. Cotton harvest technology continues to play a key role in modernization efforts in other societies[35].

While technical limitations hampered the development of mechanical cotton harvesters, social pressures of small farms and the sharecropping system stifled its adoption[36]. Many were fearful of the earliest mechanical pickers, envisioning the destruction of the South's sharecropping system and the loss of work for millions of people[37]. The major migration of 5 million people from the South for higher-paying jobs in the North between 1940 and 1960 led to a severe labor shortage[17]. While the initial adoption of the cotton picker was limited by concern for the prevailing socio-economic conditions at the time, a sharp decrease in available labor during and immediately after World War II became a major impetus for its acceptance[34].

The introduction of mechanization, particularly of harvest, increased the consolidation of fields and farms. The increased size and use of machinery introduced soil problems, such as compaction, and required greater management skill. The mechanization of cotton production increased the cost of machinery and farm operating overhead. Farm size increased to justify this outlay for machinery and to support the general farm overhead. The average cotton farm in the 1940s was about 320 ha, but by the 1970s the average size had increased to 600–800 ha, a trend that continues[17,38]. The harvesting operation had long been the decisive factor in land area one farm could manage, in cotton as well as other crops[39,40].

Additional improvements in mechanization have been realized through a host of highly effective technologies, such as fertilization, irrigation and tillage. These improvements modified the crop environment, minimizing the natural limitations of the crop and its environment. However, this increased reliance on mechanization also contributed to a greater dependence on fossil fuels, for both fuel and fertilizer, increased consolidation of farms, increased production inputs, overuse of natural resources and greater complexity of the farming system.

Lifestyle changes in the US have led to the increased consumption of convenience foods, impacting the food supply and altering agricultural production[41]. This led to the development of vertically integrated production systems, particularly of animals[10], and hastened the development of technologies supporting confinement animal production.

New barriers to production have been introduced through the intensification of animal production in confinement buildings and feedlots. Accurate identification and tracking of animals is needed to determine previous history and potential performance, and especially recognition of potential disease exposure such as bovine spongiform encephalopathy (BSE). As with monoculture crops, intensive animal production exposes animals to increased risks of some diseases, requiring changes in disease management including the increased use of antibiotics with uncertain impacts on consumers. Intensive animal production facilities also concentrate wastes which impair soil and water resources and require additional technologies to handle disposal. Moreover, the vertical integration of animal production, with its rigid top-down management and dependence on expensive animal production technologies, has left many producers frustrated from excess debt and a lack of control on their own farms[14].

### Conservation technologies

While technologies addressing genetic improvements and mechanization are driven fundamentally by a desire to improve yield, the development of conservation production systems is driven by concerns for the environment, often resulting from problems introduced from previous technologies. Conservation practices help conserve limited soil and water resources and address production problems on areas too steep or dry for conventional tillage. Reduced tillage operations and use of cover crops protect the soil surface from erosion and ultimately increase organic matter and aggregate stability to improve the soil's water holding properties[42].

In addition to the environmental benefits, conservation technologies often approach agricultural production as a system. By considering the entire agro-ecosystem, the impact of production practices on the supporting natural resource base are recognized. As the knowledge of interactions within the agricultural production system grows, appreciation for the importance of conserving the natural resource base increases. Ancillary benefits to producers include savings in time and fuel from conservation tillage systems, as well as lower capital investment in powerful tractors and tillage equipment[43].

Conversely, conservation tillage has a number of potentially significant disadvantages. Tillage is an effective mechanical form of weed control that prepares the seed bed and reduces pathogens. Without mechanical weed control, herbicide use and costs will generally increase, especially during the early transition years. The introduction of herbicide-resistant crops hastened the adoption of conservation systems, as farmers had a reliable chemical method of weed control. However, this rapid and extensive adoption has increased the development of herbicide-resistant weeds[44]. Farmers are now on a treadmill of needing new herbicide-resistant varieties to compensate for failures in the previous technology.

Increased complexity of management results from the implementation of conservation systems, as timing of operations becomes more critical. Management of cover crop residue is also a concern. Increased residue from cover crops keeps the soil wetter and cooler after planting than tilled soil, shortening the growing season. Increased residue from conservation tillage may also require changes in nitrogen management, as high levels of residue can immobilize nitrogen, limiting its availability near the seedling roots. Yield depression related to inadequate early season nitrogen may have been one of the causes for a dip in no-till use in the late 1990s[42].

Conservation technologies showed a combination of linear delivery and learning selection, with the public and private sectors providing the general outlines of the technology and farmers customizing and adapting the technology to their particular situations. Conservation tillage is adopted more rapidly by farmers with more education, larger operations, and higher incomes, and on farms with higher soil quality[45,46]. Risk-averse farmers adopt conservation tillage more slowly than risk neutral farmers to avoid higher initial costs while learning the new system[47]. Land tenure also influences adoption rates of conservation practices as cash-renters are less likely than owner-operators to adopt practices with medium term payoffs[14,48]. This may be a key finding for the future of American agriculture, as over 40% of US farmland is leased.

Perhaps the biggest boost for adoption of conservation tillage came from government programs, starting with the Conservation Compliance provisions of the 1985 Farm Bill, and continuing through subsequent farm bills. These provisions required farmers on Highly Erodible Land (HEL) to reduce erosion significantly by using an approved conservation system to maintain benefit and program eligibility. For many farmers on HEL, conservation tillage was the only feasible management system to maintain eligibility.

With continued pressure from environmental interests, social and political concerns and increasing fiscal demands, farmers will continue to explore methods to reduce costs by eliminating field operations, provided that options exist that maintain yields and profitability. With steadily improving implements, agrichemicals, and seeds adapted to higher residue levels, increased local experience, and declining social pressures against conservation tillage, conservation tillage should continue to expand, particularly where erosion is a problem, for larger, owner-operated farms and for farmers who are not strongly risk-averse. Improved methods of weed control, particularly if they are simple, would facilitate expanded use of conservation tillage for those crops and regions that have not seen much adoption to date. Modifications to future farm bills away from commodity payments towards conservation payments will likely further hasten the adoption of conservation systems.

Conservation systems have the potential to move agricultural production systems towards environmental sustainability. Environmental concerns will continue to influence governmental programs that promote conservation tillage. Baylis et al.[49] reported that even a moderate increase in adoption of conservation tillage would improve water quality enough to increase downstream recreation benefits nationally by $175 million. A large increase in the use of conservation tillage may contribute $243 million nationally for recreation alone.

### *Information systems*

Information systems are examples of technologies that were largely developed in areas other than agriculture, and have been adapted to farming. Software development and information management systems have improved the ability of the farmer to manage complex agricultural production systems, especially for record keeping and marketing of crops.

The increasing complexity in agricultural systems requires more attention to management and greater finesse in the decision making process. Increased globalization has expanded competition, requiring producers to improve their marketing skills to get the best prices for their products. While some production systems have become more vertically integrated[41], other producers have found ways to recapture income through diversification of farm enterprises in which the producer maintains control, or an economic interest in, value-added products beyond the farm gate[14]. Additionally, increased social and political pressures to minimize environmental impact have increased record keeping requirements and confounded production choices.

Information systems can help manage much larger amounts of information and encompass a variety of technologies. Some information technologies include automated detection systems, such as remote sensing, soil sampling systems, and yield monitors, that allow producers to gather physical information about their production system. These rely on global positioning systems to spatially record physical attributes. Other information systems are designed as management tools for record-keeping, and may incorporate a geographic information system for spatially recording physical and economic information about the system and help make management decisions. More complex information systems, such as crop models, rely on data about the system and make management decisions based on predictive estimates of system function. These tools can be simple, requiring a minimal amount of data collection and computer technology, or complex, requiring extensive data collection and computer expertise. Sophisticated technologies that offer the potential to improve crop management such as precision agriculture[50] are often facilitated by information technologies. As the technology has advanced, potential cost benefits from implementing precision agriculture have improved[51].

The early stages of the development of information technologies fit a linear transfer of technology model, as technology was borrowed from other disciplines such as computer engineering and adapted to agriculture. Increased intensification of farms and improvements in computer and engineering technologies led to the development of precision technologies for agriculture[50]. As the technology progresses, it is evolving into a learning selection model as more end-users are becoming involved in developing or modifying existing tools to suit their needs. However, the complexity of the systems and perceived limited or negative return on investment have hampered wide-spread adoption[52]. The learning curve for adopting information technologies can often be prohibitively steep, though as farmers' education levels increase, their use of computer technologies increases[52,53]. Simplicity of a technology and its potential to decrease risk have been identified as prime factors in the adoption of new technology[13]. The perceived absence of both of these factors is apparently limiting the rapid adoption of information systems in agricultural production. Adoption of technology is also age-related, as older farmers are less likely to adopt computers on-farm[53].

The most common information systems used by farmers are computers for financial and production record keeping and information gathering from the Internet[53]. More complicated technologies, such as crop models and decision support tools, have slower acceptance rates. As information technologies become more user-friendly and the user base becomes more knowledgeable about the potential utility of these technologies, development and adoption of information systems into agriculture are likely to increase.

In addition to their greater complexity, decision support tools rely on the knowledge of complex issues. Many of the factors impacting complex systems will not be observed through traditional reductionist research. Rather, the emergent properties of the system will only be observed in a systems research program. Future advances in the application of information technologies to agriculture may require a greater emphasis on systems research[54,55].

Information systems expand knowledge exchange through technologies such as the Internet and enhance the breadth of expertise available for identifying problems and developing solutions. Farmers now have access to more information more quickly and from a much broader range of sources than ever before. This allows them to make more rapid decisions, such as when to buy and sell products. Information technologies offer methods of integrating the disparate pieces of the production puzzle for information gathering and decision support. As the agricultural system becomes more complex, this information will be increasingly important in guiding farmers.

## Implications for Future Agronomic Technologies

Social, political and economic pressures worked in concert to shape the evolution of the current agricultural production systems in the US[10]. Technological advances, often designed to address social concerns or overcome environmental limitations, further refined agriculture. While the current US agricultural systems are unquestionably highly productive, this abundance is based on an unsustainable use of natural resources and fossil fuels. Future challenges will exacerbate an already complex system and introduce new and greater problems[56]. Emerging technologies will be needed to address issues of economic and environmental sustainability, shifts in global population and consumption patterns and competition for land use.

Since technology is developed at the leading edge of our understanding, it is difficult to anticipate the impacts of that technology on the agricultural system. Since the 1930s, increases in production efficiency from technological innovations have occurred in conjunction with substantial structural changes in farming communities as fewer people are involved in agriculture[57]. In light of changing constraints to agricultural production, questions arise as to future advances in agricultural productivity, not from the standpoint of abundance, but of sustainability[4]. How, then, do we transition the current US production system to economically and environmentally sustainable production? While it may seem appealing, it is most likely neither possible nor desirable to discontinue technological advances.

A change in philosophical approach to address sustainability may be more important than simply changing practices[54]. Innovators in agriculture, including farmers, educators, researchers, businessmen, lawmakers, and so on, need to focus on more inherently multidisciplinary approaches to solve agricultural production problems. Moreover, there must be a broader focus on problem identification and resolution, incorporating societal, political and global goals of environment and nutrition together with producers' financial goals. In developing an economically and environmentally sustainable agricultural agenda, society must be willing to compromise its expectations, since current consumption levels of agricultural products, and the natural resources they require, are not sustainable[58]. New approaches to technology development and delivery have the potential to accommodate these needs by establishing a broad network of individuals with a diverse range of expertise, and working closely with the end users to identify goals, delineate problems and develop solutions[9].

Although the US has succeeded in developing an inexpensive, efficient food production and delivery system, over-consumption and lowered nutritional value have negative impacts on soil and water resources and human health[59]. Globalization makes a variety of foods available year round, but increases hidden costs due to transportation and compromises flavor and nutrition[60]. Food in the US is readily available and inexpensive in part because we have ignored the costs of natural resource depletion and non-renewable fossil fuel use in calculating the costs of production. While the caloric content of available food has increased worldwide, increased globalization and concentration of the food system has reduced local production of crops and limited distribution, access and future food options[61]. Exploring the linkages between food, health, agriculture and the environment requires a different philosophical approach to agricultural production than a simple focus on yield[16], and is becoming an increasingly important component of the social environment influencing farming[5].

The current production system is not economically sustainable for farmers. Prices paid to US farmers have not kept pace with the cost of agricultural inputs (Fig. 1b)[2]. The unfavorable price shifts force increases in farm size, limit investment in agriculture and lead to political pressure for substantial farm programs to support agriculture and rural communities[5].

The world's growing population and increasing income imply increased demand for agricultural goods. Contrary to Malthusian expectations[62], however, to date supply has increased faster than demand. Currently, more than four people are fed per hectare of cultivated land, with just over 20 people being supported per irrigated hectare (Fig. 1c)[63]. Estimates of future population growth and rates of cultivated land use indicate a slow increase in population per unit of irrigated land[63,64], limiting the demand for agricultural products worldwide[65].

The integrated worldwide outcome of all factors affecting agriculture shows a rising historical trend in food production per capita (Fig. 1d)[2], which is projected to continue[63]. Rosegrant et al.[63]analyzed a number of future scenarios and found that, across a range of assumptions, agricultural supply is likely to keep pace with demand, resulting in similar or lower prices for agricultural goods out to the year 2020. While technology has helped realize this abundance, future advances will require a different mindset to better balance environmental and production goals and keep agricultural production economically viable.

Previous biological advances have come about largely from increases in the genetic potential of crops. Advances in biotechnology have expanded our ability to modify crop behavior beyond the range of conventional breeding techniques, improved quality and quantity of agricultural products, and incorporated unique value-added traits in newly-released cultivars. Future genetic advances will most likely come from value-added traits, such as neutraceutical and pharmaceuticals; addressing environmental constraints arising from agricultural intensification (soil erosion, water logging and salinity, coevolution of pests and pathogens, global climate change, loss of biological diversity, and limited water supply), and political, financial and human resource issues[4,66]. Additional benefits from advances in genetic technologies will allow improved identification and incorporation of superior traits and increased food safety through improved testing methods.

Improvements in mechanization have increased production output with fewer people, and improved the safety of farm workers. Future advances in mechanization will have to address power requirements of agriculture and the current reliance on fossil fuels. Additional engineering advances have the potential to conserve natural resources through more accurate application, and by better matching inputs with potential output. Improvements in harvest, processing and storing can retain nutritional value and enhance societal access to products.

Conservation systems address environmental, social and political concerns, and, where implemented, have made significant gains towards remediation of environmental damage. Conservation practices will continue to evolve and redefine environmental sustainability and impacts while maintaining production capacity. Future advances in environmental sustainability will come from greater implementation of conservation technologies, increasing the scope of conservation tools and practices to reduce reliance on non-renewable resources and chemical controls, and greater use and reuse of waste products from both agriculture and society.

Information technologies have the potential to address increasingly complex management issues by providing decision support tools for farmers. Additional information technologies will allow tracking products from start to finish and remote monitoring of crops and animals. The enhanced tracking of production will also allow better knowledge of chemical use and application, and prediction of potential environmental impacts. Marketing tools and internet access will assist producers in the global marketing of products.

On a larger scale, our definition of agriculture may change. Agriculture can be defined as the process of using natural resources (sunlight, air, water and soil) to produce a consumable product (e.g. food, fuel and fiber), while maintaining sufficient resources for the next generation. This definition could include alternative production systems such as wind turbine farms[67], which do not involve cultivation of the soil but do tie up a valuable natural resource (land) in the production of a consumable item (power). Similarly, ecosystem services, such as the buying and selling of carbon credits, are potential agricultural products[68]. As energy constraints and ecosystem services continue to escalate in importance, the management of the land for these purposes may surpass our current limited view of agricultural products.

Future production systems will need to be flexible to respond to rapid changes in climate and uncertainties in global markets from shifts in politics, production and population. In addition to addressing growing environmental concerns, sustainable farming systems will need to address energy concerns required for both agricultural production and as potential agricultural products.

An agricultural production system has been suggested that allows for dynamic responses to external pressures[57]. This dynamic management philosophy coupled with multiple cropping enterprises allows farmers to incorporate changes in their production system in response to changing needs. A dynamic system would be able to accommodate the increasingly complex factors influencing farmers today and reduce risks of production. Integrated farming systems allow producers to optimize an array of factors, including environmental and financial, rather than simply focusing on yield alone. By carefully examining current production systems and the influences that have shaped them, we can develop future technologies that will address sustainability with the needs of farmers, society and the environment in mind.

## References


1 Food and Agriculture Organization (FAO). 2006. The FAOSTAT Database. Available at Web site http://faostat.fao.org/default.aspx (verified 5 September 2007).

2 NASS. 2006. Prices received by Farmers, Indexes. Available at Web site http://www.nass.usda.gov/index.asp (verified 5 September 2007).

3 Strauss, S. 2002. Best in breed ..... has nothing to do with biotech. The Globe and Mail. Toronto, Ontario. 26 January 2002. Available at Web site http://www.mindfully.org/GE/GE4/No-Biotech-Best.htm (verified 5 September 2007).

4 Naylor, R.L. 1996. Energy and resource constraints on intensive agricultural production. Annual Review of Energy and the Environment 21:99–123.

5 Archer, D.W., Dawson, J., Kreuter, U.P., Hendrickson, M., and Halloran, J.M. 2008. Social and political influences on agricultural systems. Renewable Agriculture and Food Systems 23(4):272–284.

6 Cochrane, W.W. 1958. Farm Prices: Myth and Reality. University of Minnesota Press, Minneapolis.

7 Petroski, H. 1992. The Evolution of Useful Things: How Everyday Artifacts—From Forks and Pins to Paperclips and Zippers—Came to be as they are. Alfred A. Knopf, Inc., New York.

8 Douthwaite, B., Keatinge, J.D.H., and Park, J.R. 2002. Learning selection: an evolutionary model for understanding, implementing and evaluating participatory technology development. Agricultural Systems 72:109–131.

9 Hagel, J. and Brown, J.S. 2005. From push to pull—emerging models for mobilizing resources. Working Paper, October, 2005. Available at Web site http://www.johnseelybrown.com/pushmepullyou4.72.pdf (verified 5 September 2007).

10 Hendrickson, J., Sassenrath, G.F., Archer, D., Hanson, J., and Halloran, J. 2008. Interactions in integrated agricultural systems: the past, present and future. Renewable Agriculture and Food Systems 23(4):314–324.

11 Sumberg, J. and Reece, D. 2004. Agricultural research through a 'New Product Development' lens. Experimental Agriculture 40:295–314.

12 Flora, C.B. 2004. Agricultural change and rural development. Rural Development News 27(3):1–3. Available at Web site http://www.ag.iastate.edu/centers/rdev/newsletter/Vol27No3-2004/agchange.htm (verified 5 September 2007).

13 Batz, F.-J., Peters, K.J., and Janssen, W. 1999. The influence of technology characteristics on the rate and speed of adoption. Agricultural Economics 21:121–130.

14 Sassenrath, G.F., Hanson, J., Hendrickson, J., and Archer, D. 2007. Principles of dynamic integrated agricultural systems: lessons learned from an examination of Southeast production systems. In P. Bohlen (ed.). Agro-ecosystem Management for Ecological, Social, and Economic Sustainability. Taylor and Francis/CRC Press, UK, in press.

15 Watson, R.T., Zinyowera, M.C., and Moss, R.H. 2006. IPCC Special Report on The Regional Impacts of Climate Change. An Assessment of Vulnerability. Intergovernmental Panel on Climate Change. Available at Web site http://www.grida.no/climate/ipcc/regional/index.htm (verified 5 September 2007).

16 Welch, R.M. and Graham, R.D. 1999. A new paradigm for world agriculture: meeting human needs. Productive, sustainable, nutritious. Field Crops Research 60:1–10.

17 United States Bureau of the Census. 1975. Historical statistics of the United States: colonial times to 1970. Government Printing Office, Series C 55–62, p. 93–95.

18 Executive Summary of the EPA's Organophosphate Pesticides: Revised Cumulative Risk Assessment. 2002. Available at Web site http://www.epa.gov/pesticides/cumulative/rra-op/Executive_Summary-pdf.pdf (verified 5 September 2007).

19 Halloran, J.H. and Archer, D. 2008. External economic drivers and integrated agricultural systems. Renewable Agriculture and Food Systems 23(4):296–303.

20 Brown, W.L. 1984. Hybrid vim and vigor. Science 845(9): 77–78.

21 Tracy, W.F., Goldman, I.L., Tiefenthaler, A.E., and Schaber, M.A. 2004. Trends in productivity of US crops and long-term selection. Plant Breeding Reviews 24(2):89–108.

22 Myers, K.H. 1933. Methods and costs of husking corn in the field. Farmers' Bulletin 1715. USDA, Washington, DC.

23 Kneen, B. 1999. Restructuring food for corporate profit: the corporate genetics of Cargill and Monsanto. Agriculture and Human Values 16:161–167.

24 Benbrook, C. 2003. Principles governing the long-run risks, benefits, and costs of agricultural biotechnology. Conference on Biodiversity, Biotechnology, and the Protection of Traditional Knowledge held on 5 April 2003. Available at Web site http://www.biotech-info.net/biod_biotech.pdf (verified 5 September 2007).

25 Chassy, B.M., Parrott, W.A., and Roush, R. 2005. Crop biotechnology and the future of food: a scientific assessment. CAST Commentary. QTA 2005-2 October 2005. Available at Web site http://www.biotech.ucdavis.edu/PDFs/CAST%20Report%20-%20Crop%20Biotechnology%20and%20the%20Future%20of%20Food%2011-05.pdf (verified 5 September 2007).

26 DeGregori, T.R. 2004. Origins of the Organic Agriculture Debate. Iowa State Press, Ames, Iowa. p. 211.

27 Stabinsky, D. and Cotter, J. 2004. Rice: genetically engineered rice—not sustainable agriculture. Greenpeace International, The Netherlands. Available at Web site http://www.greenpeace.org/raw/content/international/press/reports/genetically-engineered-rice-n.pdf (verified 5 September 2007).

28 Pardo, R. and Calvo, F. 2006. Are Europeans really antagonistic to biotech? Nature Biotechnology 24:393–395.

29 Foote, R.H. 2002. The history of artificial insemination: selected notes and notables. American Society of Animal Science 1–10. Available at Web site http://bio.cc/Biohistory/artificial_insemination_of_livestock_1950.pdf (verified 5 September 2007).

30 Thibier, M. and Wagner, H.-G. 2002. World statistics for artificial insemination in cattle. Livestock Production Science 74:203–212.

31 Funk, D.A. 2006. Major advances in globalization and consolidation of the artificial insemination industry. Journal of Dairy Science 89:1362–1368.

32 Mariola, M.J. 2005. Losing ground: farmland preservation, economic utilitarianism, and the erosion of the agrarian ideal. Agriculture and Human Values 22:209–223.
33 White, W.J. 2001. Economic history of tractors in the US. In R. Whaples (ed.). EH Net Encyclopedia. 15 August 2001. Available at Web site http://eh.net/encyclopedia/article/white.tractors.history.us (verified 5 September 2007).
34 Holley, D. 2000. The Second Great Emancipation: The Mechanical Cotton Picker, Black Migration, and How They Shaped the Modern South. University of Arkansas Press, Fayetteville.
35 McClintic, D. 2003. China's big dilemma. Available at Web site http://www.deere.com/en_US/ag/pdf/furrow/2003-summer-article.pdf (verified 6 June, 2007).
36 Lemann, N. 1992. The Promised Land: The Great Black Migration and How it Changed America. Vintage Books. p. 408.
37 Holley, D. 2003. Mechanical cotton picker. In R. Whaples (ed.). EH Net Encyclopedia. 17 June 2003. Available at Web site http://eh.net/encyclopedia/article/holley.cottonpicker (verified 5 September 2007).
38 United States Department of Agriculture, Economic Research Service. 1974. Statistics on Cotton and Related Data, 1920–1973. Statistical Bulletin No. 535. Government Printing Office.
39 Grimes, W.E., Kifer, R.S., and Hodges, J.A. 1928. The effect of the combined harvester-thresher on farm organization in southwestern Kansas and northwestern Oklahoma. Kansas Agricultural Experiment Station. Contribution No. 45. Available at Web site http://www.oznet.ksu.edu/historicpublications/pubs SC142.pdf. (verified 5 September 2007).
40 Martin, S. and Cooke, F. Jr. 2002. Mississippi Delta cotton farm structure 2002. Delta Ag Econ News. Summer. 2002. Available at Web site http://www.msstate.edu/dept/drec/archive/delta_ag_econ_news/agnews8.htm (verified 5 September 2007).
41 Martinez, S. and Stewart, H. 2003. From supply push to demand pull: agribusiness strategies for today's consumers. Amber Waves. Available at Web site http://www.ers.usda.gov/Amberwaves/November03/pdf/supplypush.pdf (verified 5 September 2007).
42 Martens, D.A. 2001. Nitrogen cycling under different soil management systems. Advances in Agronomy 70:143–192.
43 Martin, S.W., Robinson, J.R.C., Cooke, F.T. Jr, and Parvin, D. 2005. Managing tillage, crop rotations, and environmental concerns in a whole-farm environment. Crop Management. Online at http://www.plantmanagementnetwork.org/cm/
44 Osteen, C. and Livingston, M. 2006. Pest management practices. In Agricultural Resources and Environmental Indicators, 2006 Edition/EIB-16. p. 107–115. Economic Research Service, US Department of Agriculture, Washington, DC.
45 Fuglie, K.O. and Kascak, C.A. 2001. Adoption and diffusion of natural resource conserving technology. Review of Agricultural Economics 23:386–403.
46 Napier, T.L., Tucker, M., and McCarter, S. 2000. Adoption of conservation production systems in three Midwest watersheds. Journal of Soil and Water Conservation 55:123–134.
47 Bosch, D.J. and Pease, J.W. 2000. Economic Risk and Water Quality Protection in Agriculture. Review of Agricultural Economics 22:438–463.
48 Soule, M.J., Tegene, A., and Wiebe, K.D. 2000. Land tenure and the adoption of conservation practice. American Journal of Agricultural Economics 82:993–1005.
49 Baylis, K., Feather, P., Padgitt, M., and Sandretto, C. 2002. Water-based recreational benefits of conservation programs: the case of conservation tillage on US cropland. Review of Agricultural Economics 24:384–393.
50 Stafford, J.V. 2000. Implementing precision agriculture in the 21st century. Journal of Agricultural Engineering Research 76:267–275.
51 Martin, S.W., Hanks, J., Harris, A., Wills, G., and Banerjee, S. 2005. Estimating total costs and possible returns from precision farming practices. Crop Management. Online at http://www.plantmanagementnetwork.org/cm/
52 Adrian, A.M., Norwood, S.H., and Mask, P.L. 2005. Producers' perceptions and attitudes toward precision agriculture technologies. Computer and Electronics in Agriculture 48:256–271.
53 Batte, M.T. 2005. Changing computer use in agriculture: evidence from Ohio. Computers and Electronics in Agriculture 47:1–13.
54 Ikerd, J.E. 1993. The need for a systems approach to sustainable agriculture. Agriculture, Ecosystems and Environment 46:147–160.
55 Aldy, J.E., Hrubovcak, J., and Vasavada, U. 1998. The role of technology in sustaining agriculture and the environment. Ecological Economics 26:81–96.
56 Hanson, J.D., Hendrickson, J., and Archer, D. 2008. Challenges for maintaining sustainable agricultural systems. Renewable Agriculture and Food Systems. 23(4):325–334.
57 Hendrickson, J.R., Hanson, J., Tanaka, D.L., and Sassenrath, G. 2008. Principles of integrated agricultural systems: introduction to processes and definition. Renewable Agriculture and Food Systems. 23(4):265–271.
58 Mayo, E., Knight, A., Clifton, R., Jackson, T., Johnstone, J., Furey, S., Lee, A., and Pomfret, C. 2006. I Will if You Will. Towards Sustainable Consumption. Sustainable Development Commission. Available at Web site http://www.sd-commission.org.uk/publications.php?id=367 (verified 5 September 2007).
59 Blair, D. and Sobal, J. 2006. Luxus consumption: wasting food resources through overeating. Agriculture and Human Values 23:63–74.
60 Wilkins, J.L. 2005. Eating right here: moving from consumer to food citizen. Agriculture and Human Values 22:269–273.
61 Koc, M. and Dahlberg, K.A. 1999. The restructuring of food systems: trends, research, and policy issues. Agriculture and Human Values 16:109–116.
62 Ehrlich, P.R. 1971. The Population Bomb. Ballantine Books, New York.
63 Rosegrant, M.W., Paisner, M.S., Meijer, S., and Witcover, J. 2001. Global Food Projections to 2020: Emerging Trends and Alternative Futures. International Food Policy Research Institute, Washington, DC.
64 Rosegrant, M.W., Cai, X., and Cline, S.A. 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington, DC.
65 Johnson, D.G. 1999. The growth of demand will limit output growth for food over the next quarter century. Proceedings of the National Academy of Sciences, USA 96:5915–5920.

66 Trewavas, A.J. 2001. The population/biodiversity paradox. Agricultural efficiency to save wilderness. Plant Physiology 125:174–179.

67 Donavan, L. 2005. Permit sought for wind farm. Bismarck Tribune, Bismarck, North Dakota, 26 October 2005. Available at Web site http://www.bismarcktribune.com/articles/2005/10/26/news/local/104446.txt (verified 5 September 2007).

68 Bricklemyer, R.S., Miller, P.R., Turk, P.J., Paustian, K., Keck, T., and Nielsen, G.A. 2007. Sensitivity of the Century model to scale-related soil texture variability. Soil Science Society of America Journal 71:784–792. Available at Web site http://soil.scijournals.org/cgi/reprint/71/3/784 (Verified 5 September 2007).