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# The Lessons of Fermentation for the New Bio-Economy

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The modern bio-economy consists of biotechnology, green chemistry, and modern biofuels, and can learn from the experience of the "traditional" bio-economy that relied on processes such as fermentation to alcoholic drinks, foods, and medicine. The traditional bio-economy expanded the range of locations that humans could survive and what they could grow. Lessons of the traditional biotechnology are likely to apply to the modern one. The new bio-economy will require moving outside of our comfort zone and may require us to take calculated risks, but within a technological framework we can control and mitigate these risks. The evolution of the new biotechnology will encounter resistance, but its potential is so vast that it is likely to prevail.

***Key words:*** Agricultural biotechnology, bio-economy, biofuel, fermentation, GMO.

The bio-economy consists of industries that apply microbiological processes to produce commercial products (Enriquez-Cabot, 1998). Agriculture was a key element of the 'traditional' bio-economy, and fermentation has had an important role on the traditional bio-economy. It has been used to produce wine, beer, and cider; to create leaven bread and lactic acid to preserve; and to produce sausages or yogurt (see Table 1 for further examples). As one of human's earliest form of food preservation technology, fermentation enabled the move from perishable crops to preserved products. The 'new' bio-economy was established mostly after the 1970s and followed new discoveries of molecular and cell biology, particularly that of DNA. It includes several major subsectors including biotechnology (both agricultural and medical), biofuels, and green chemistry. The 'old' or 'traditional' bio-economy has many important lessons that are relevant to the new bio-economy. First, we will outline the many benefits associated with fermentation. Second, we will explore some of the regulatory challenges that products generated by fermentation (like wine and beer) have faced and their implications for biotechnology. Then we will address the importance of supply chains and disease control in the traditional bio-economy and their lessons for supply chain and product development in the new bio-economy.

## Gains from Fermentation

Fermentation expanded the range of products that are derived from agricultural crops. One of the main advantages of fermentation is that it allowed for the production of storable food products in early times when storage technologies were limited and spoilage was a major problem. Agricultural production in many regions is seasonal, where much of the output is harvested during a short period of time (Battcock & Azam-Ali, 1998). Crops like grains have storage capacities, but many fruits and vegetables are perishable. Some areas also may have limited capacity to hold agricultural products that are storable, like grains. So by converting otherwise perishable food products—like grapes into wine and pickling various foods—fermentation allowed the improvement of welfare during winters or less productive seasons. We present a very simple model of the gains from fermentation based on Lichtenberg and Zilberman's (2002) framework that is summarized in Figure 1.

For the sake of simplicity, the outputs of fermentation and fresh production are presented in equivalent units. We separate demand during the summer (harvesting season) and during the winter (the rest of the year). The demand in the winter may be higher because the rest of the year is much longer than the harvesting season (also, winter is cold and there is more demand for food). The initial supply of food at the summer is very high while the initial supply of food at the winter is very low. The initial equilibrium before fermentation is available is presented at Point B for the summer and Point A for the winter. Fermentation will reduce the supply during the summer and increase supply during the winter, thus fermentation allows movement from Point AB to Point CD. The welfare gain from fermentation is equal to the area MACN minus the area TDBR. One can show that the gain is greater the greater the *productivity of fermentation*, because it enables the reduction of the fresh harvest allocated to fermentation, which would lead to increases in the amount of fresh output available during the summer. The gains from fermentation increases are

**Table 1. Fermented foods from around the world.**

| Region | Examples of fermented foods |
|---|---|
| **Americas** | Cucumber pickles, dill pickles, olives, sauerkraut, lupin seed, oilseeds, vanilla, wines |
| **Europe** | Olives, sauerkohl, sauerruben, grape vinegar, wine vinegar, wines, citron |
| **Indian subcontinent** | Pickled fruits and vegetables, wine, beverages (acar, achar, tandal achar, garam nimboo achar, gundruk) |
| **Southeast Asia** | Fermented vegetables (bai-ming, leppet-so, miang, nata de coco, nata de pina) |
| **East Asia** | Fermented vegetables and fruits (kimchi, cha-ts'ai, hiroshimana, jangagee, nara senkei) |
| **Africa** | Pickled vegetables and seeds (lamoun makbouss, mauoloh, msir, mslalla, olive, oilseeds, ogili, ogiri, hibiscus seed) |
| **Middle East** | Pickled fruits and vegetables (tamoun makbouss, mekhalel, olives, torshi, tursu) |

*Source: Campbell-Platt (1987)*

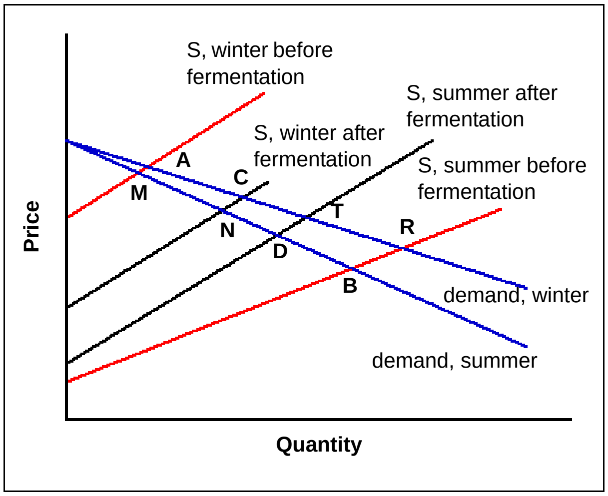


**Figure 1. Impacts of fermentation on supply and demand.**

greater the lower the supply of food during the winter months. That may explain why there has been much heavier emphasis on pickling in regions with severe winter periods, such as Russia. While the analysis was presented in the context of a market economy, the main lessons of the model apply to fermented products that were produced mostly for home consumption of poor households with some excess supply bartered or in local markets.

A major advantage of fermentation activities is that they enhanced humans' ability to overcome seasonality constraints, which allowed for the expansion of areas where humans could survive and thrive. But fermentation also allowed for the production of products that provided other benefits. In the field of medicine, alcohol has been used as an antiseptic and a solvent.[1] People realized that when water quality is poor, alcohol functioned as a safe substitute, even before people were aware of germs and hygiene (Phillips, 2002). The most important contribution of fermented products (such as alcohol) in the field of medicine is that it provided a means to overcome pain, especially in earlier days when anesthesia and other pain management solutions did not exist.

The new bio-economy is generating products that provide similar benefits. First, modern applications of fermentation are part of the new bio-economy. A major industrial application of fermentation is in the production of ethanol from sugars derived from sugarcane, corn, or even cassava. Fermentation is also the basis for large-scale production of medicines, like antibiotics. However, the distinguishing feature of the modern bio-economy is the use of new knowledge in molecular and genetic biology and its applications in biotechnology. The most dramatic benefits of biotechnology have been in the field of medicine, yet it also holds a lot of promise to food and agriculture. We will concentrate here on genetically modified varieties (GMV), mostly in farming. Genetic modification is also expanding traditional fermentation by introducing genetically modified enzymes in cheese and beer production.

The use of GMVs in agriculture has already yielded significant benefits. Thus far, GMVs have mostly been used for pest control. In *developed* countries, they frequently replace pesticide chemicals and reduce the environmental health effects associated with pesticide use, while in *developing* countries they increase yield by overcoming pest problems (Qaim & Zilberman, 2003). In addition to substitution for pesticide and increased yield, one of the main benefits of GMVs is that it allowed for the expansion of the range of locations where crops can grow (Lichtenberg & Zilberman, 1984). One obvious example is the expansion of soybeans in Argentina as a result of the control of late season weeds using herbicide-resistant varieties (National

1. *In the 16th Century, the Swiss physician Paracelsus popularized the use of distilled alcohol as a solvent to prepare tinctures from herbs and chemicals (Marshall & Marshall, 2005).*

Research Council [NRC], 2010). Aside from controlling pests, GMVs affect other aspects of agricultural activities. There is also evidence that some GMVs improve crop storability (Wu, 2006). There is ongoing research on drought-tolerant varieties that will enable both retention of production in areas afflicted by rising temperatures and even expand it to regions that have not been farmed before (Zilberman, Sexton, Dalton, & Pray, 2011).

In addition to expanding the locations where crops can be grown, the capacity to insert genetic traits to existing varieties through transgenic technologies may lead to the restoring of production of varieties that have been abandoned because of disease and even the reintroduction of certain crops to regions when they are not grown due to pest problems (Zilberman, Ameden, & Qaim, 2007). Thus, the new biotechnology will enable agriculture to overcome space constraints much like fermentation has done.

## No Pain, No Gain

Alcoholic beverages are probably the most well-known, widely used fermented products, and they have been quite controversial. Both their merits and shortcomings are well known. Throughout millennia, the virtues of wine were celebrated. The Bible says, "*wine which cheereth God and man*"(Judges 9:13), and at the same time it also says "*wine is a mocker, strong drink is raging: and whoever is deceived thereby is not wise*" (Proverbs 20:1). The benefits of alcoholic drinks are that they taste good, improve moods, relieve pain, and provide nourishment and disinfection. More quantitative assessments of these benefits are needed, but it is clear that these benefits are substantial because they have to compensate for the many drawbacks of alcohol. One of these drawbacks is that overconsumption may harm human health.[2] Alcohol may contribute to significant numbers of deaths directly or indirectly. It may alter behavior and result in accidents, fights, and other mishaps.[3] The negative side effects of alcohol led to a variety of policies to control it. Several religions ban alcoholic beverages; for example, Islam and the Church of Jesus Christ of Latter-day Saints.

Banning alcohol, from the experience of the United States,[4] has had many drawbacks. Lack of a legal supply lead to the development of a black market and provided a market niche for organized crime. One of the lessons that the case of alcohol provides for the new bio-economy is the futility of banning. Banning is optimal if the marginal cost of even a small level of consumption is very high.[5] In principle, even when the cost of alcohol is high, there must be an internal solution where some positive level of alcohol consumption is optimal. The thinking that might have lead to banning may reflect a 'precautionary principle' that aims to prevent people from utilizing a resource that may be 'bad' for them. But as Cardinal Richeleu is quoted as saying, "if God forbade drinking, would He have made wine so good?" The same holds for GMVs: they may entail some risk, but as we argued before they have already provided numerous benefits, and as our knowledge of their use increases, their benefits may increase. Currently, alcohol in the United States is legal but is regulated. The policies affecting alcohol have several forms. First, restrictions based on age and the type of activities you can engage in while using alcohol exist—for example, setting age limits and banning driving under the influence. Secondly, there are informational policies that warn consumers about the risks associated with alcohol consumption. Finally, alcohol consumption has been taxed both as an incentive to reduce consumption and a source of revenue. Of course the optimality of regulation has to be evaluated and policies controlling liquor should be modified accordingly.

Because of the perceived side effects, the new bio-economy has to be regulated but its regulation has to take into account benefits and costs. As in the case of the traditional bio-economy, having strict regulation for the sake of 'precaution' is costly because of the benefits lost. Graff, Zilberman, and Bennett (2009) demonstrate that having highly strict regulations of GMVs has led to the stifling of innovation, and the ban of GMVs in Europe in 1999 has led to the contraction of the biotechnology industry. Bradford, Van Deynze, Gutterson, Parrott, and Strauss (2005) have shown that strict regulation of GM traits has prevented the introduction of new GMVs in specialty crops. Furthermore, strict and costly regulation is leading to high concentration of the indus-

2. *http://www.niaaa.nih.gov/Publications/AlcoholAlerts/Pages/default.aspx*
3. *About 50% of all deaths from motor vehicle traffic accidents and homicides and 25-35% of suicides are attributable to alcohol (Sloan, Reilly, & Schenzler, 1994).*
4. *Prohibition was ratified via the 18th Amendment to the Constitution on January 16, 1919. It was repealed via the 21st Amendment to the Constitution on December 5, 1933.*
5. *Converging to infinity.*

try since smaller firms may not have the resources to afford expensive testing and development costs.

While we have heavy regulation of agricultural biotechnology, medical biotechnology—while regulated—has been allowed to flourish. One major difference has been that the benefits of medical biotechnologies are much more apparent and therefore society was willing to take extra risks associated with their development and use, which is similar to the case of alcohol. Since consumers were aware of the benefits of alcohol in many cases, they were willing to take the risk associated with its consumption. In the case of agricultural biotechnology, the perceived risks seem large—some due to misinformation and negative campaigns—so the benefits of GMVs are not very apparent, which has led to very strict regulation. These regulatory constraints may be loosened, as there is growing awareness of the benefits of biotechnology and appreciation of its performance. However, the regulatory restrictions limit introduction of new traits (Graff et al., 2009) and reduce opportunities for the technology to prove itself. In spite of these restrictions, Sexton and Zilberman (2011) showed that the introduction of GM traits in corn and soybeans has had a supply expansion effect that reduced the price of these agricultural commodities and served to counter the price-increasing effect of biofuels. They also argued that if these technologies were adopted in other crops and in other countries, they would lead to a further reduction in food prices. However, the resistance to introduction of GMVs in Europe is very strong and the appreciation of their benefits is not widely shared, and thus, the technology is underutilized.

## Fermentation and Product Differentiation

One of the characteristics of fermented products is their wide range of differentiation. Wines are differentiated by varietals as well as appellation, vintage, brand, and quality. Thus there are altogether thousands—possibly more—of different types of wine that reflect both differences in their production of the raw material as well as differences in processing. Similarly, there are numerous beers that can be divided again according to quality of raw materials as well as processing techniques.[6] There are also hundreds of different types of fermented foods, including kimchi, yogurts, etc. (Tamang, 2011).

There is significant literature on hedonic prices of beer and wine (Bombrun & Sumner, 2003; Golan & Shalit, 1993), reflecting significant premiums on product attributes and appellations. As Rosen (1974) suggests, differentiation among individual by income and taste will lead to differences in willingness to pay for products of different quality. Firms take advantages of these differences, resulting in a large range of differentiated products. Since income distributions are such that there are a relatively large number of people with modest means and a much smaller number of people with high incomes, as well as economics of scale in production, the product mix will consists of several mass-produced relatively low-price beers and wines and many boutique products that are aimed to niches with a higher willingness to pay. This is most apparent in the beer market, where the top four best selling beers are aimed at mass consumption at low price levels.[7] This differentiation of wine results in a small percentage of the volume of wine accounting for a large share of the revenue.[8] For example, in 2003 'premium' wines accounted for 32% of total wine revenues although they only accounted for 8% of the total volume of wine produced.

Heterogeneity and some product differentiation exists in some cases within the new bio-economy. In the case of agricultural biotechnology, there are two major GM traits that have been widely adopted: control of insects by Bt and control of weeds by herbicide-tolerant varieties. These traits have been inserted into hundreds of varieties and thus constitute one of the major advantages of GMVs: they allow you to maintain biodiversity (Zilberman, Ameden, Graff, & Qaim, 2004). In spite of this heterogeneity of varieties with modern traits, the number of crops to which GM traits have been applied is very small. The reasons are both because technologies are heavily regulated as well as young. Real product diversity will occur in agricultural biotechnology when the *number* of traits that are adopted is numerous and they are introduced to a wide range of crops. The work of Graff et al. (2009) suggests that there are many traits on the shelf, but they are constrained because of regulation. Regulation has limited the introduction of genetically modified traits to four crops that are not eaten directly by humans: corn, soybean, cotton, and rapeseed. In addition to the de facto ban on the introduction of transgenic traits into many crops and in many countries, the regulatory requirements are very costly and

6. *http://www.brewersassociation.org/pages/business-tools/craft-brewing-statistics/beer-sales*

7. *http://www.breweryage.com/stats/Stats%203-06.pdf*

8. *http://academyofwinebusiness.com/wp-content/uploads/2010/05/AnalyzingUSRetail.pdf*

that makes the introduction of varieties uneconomical even without restrictions. Furthermore, intellectual property constraints may also prevent the introduction of GMVs (Graff, Cullen, Bradford, Zilberman, & Bennett, 2003).

The diverse range of products of fermentation is a result of the long history of use of the basic fermentation procedures that led to the accumulation of a wide base of knowledge and development of numerous practices that allow diversity of products. There are likely to be low proprietary barriers to various fermentation techniques because much of the well-established knowledge about fermentation is not proprietary, as there are limits to the life of patents, and trade secrets leak over time. Similarly, the regulatory barriers on developing new fermentation technologies are not likely to be as forbidding as in the case of GMVs because of the long history of the use of fermentation, which has resulted in reduced uncertainty and is likely to lead to lower regulatory pressure.

Agricultural biotechnology is relatively young with a relatively small stock of innovations. Much of its crucial process innovations (e.g., agro bacterium) are still proprietary and the regulatory burden is severe. The barriers on innovations are likely to decline over time if the technology maintains significant records of safety and as its benefits become more apparent. Less restrictive regulations will result in lower costs of development and commercialization of existing traits and more investment in research to develop new traits. Thus over time, we expect the emergence of a wide range of traits that will be diverse in terms of the problems they address and the crops with which they are used. Koeppel (2008), for example, suggests that GMVs are likely to provide solutions to the diseases and production problems afflicting bananas, a major source of nourishments to tens of millions of people.

Research on innovation and productivity (Sunding & Zilberman, 2001) suggests that technology is frequently utilized first by applications in which it is most profitable. The early applications are very important because they develop the tools that can be used later for applications that may be less profitable. In the case of fermentation, French wines were mostly refined to meet the taste of the rich English and Dutch (Johnson, 1998). On the other end, Scully (1995) suggests that during the Middle Ages, standardized beer products were developed to enable mass consumption to meet the needs of the masses in England and the Low Countries. In both cases, revenues from lucrative markets enabled the technology to trickle down. In the case of GMVs, the early applications were low-lying fruits—pest control applications that can be sold in mass markets. These applications lead to the development of procedures that can be used later in less lucrative markets. One example is Golden Rice, which enriches rice consumed by the poor with Vitamin A. Thus, both history and economics imply that the expectation that GMVs will be developed to meet the needs of the poor first is not realistic. Subsidization of such applications are likely to enhance their emergence, but market forces will lead the emergence of these applications in areas that are most profitable in terms of reduced effort and large market potential. Once the stock of knowledge is established and there is a large base of applications, GMV products will become more diverse and are more likely to target smaller, less profitable niches.

## Residue Management and Disease Control

Not all the material of the plants that provide the input for fermentation is utilized in the process. There are residues and it may add to the profitability of the fermented product if it can provide extra value rather than incur extra cost. For example, pomace is the skin, pulp, and seeds from grapes or olives that is left after pressing for wine, juice, or oil. This product can be used as a highly valuable fertilizer or for the production of citric acid (Hang & Woodams, 1985). The byproduct of corn ethanol is dried distillers grain (DDG), which is used for animal feed. Thus, one of the lessons of the old bio-economy is that it generates multiple products and the more advanced applications are able to obtain value from most of the organisms used as inputs. Thinking in terms of multi-products is likely to be very important in the new bio-economy, be it for the production of second-generation biofuels or in green chemistry. The environmental economic literature emphasizes that residue can be a source of pollution, and both pollution control consideration and simple profitability consideration suggest the value of technology packages that increase the utilization of input and reduce residue (Khanna & Zilberman, 1997). Emphasis on development of such technologies should be a major priority as the new bio-economy is evolving.

Since fermentation is based on the use of living organisms, it has to operate in conditions that allow them to thrive and survive and have to evolve constantly to address disease problems. Disease control can be done by practices that will assure maintaining favorable environments as well as pursuing biological research that will identify new strains of yeast that are able to withstand changing conditions (Jones & Greenfield, 1982). Furthermore, like any agricultural activity, expanding the genetic base of fermentation allows for expansion of where and how it can be produced. For example, traditional (older) beers were ales that required fermentation in hot temperatures. But, the discovery of a new type of yeast lead to the development of a new type of beer—lager—which could be fermented in colder environments. However, the discovery of the cold-tolerant beer took generations and it was a result of the discovery of America, where the essential organism was discovered (Libkind et al., 2011). But with the new biotechnology and the function of genomic research, it will be much easier to detect the genetic traits that lead to desirable performance, and fermentation technologies can be improved with the use of new biotechnology tools. Thus, the modern bio-economy will help the traditional one.

The need to address evolving damages from diseases and pests will be a crucial element of the new biotechnology. Already some of the new GM traits are susceptible to a buildup of resistance (NRC, 2010). Disease control can be addressed by the development of practices that will protect against damage control agents and discovery of genetic traits that can withstand diseases. That will suggest that the new economy will require continuous infrastructure of research and education to support it as well as a system of monitoring regulation and training that will identify diseases and implement solutions to control them. The new bio-economy then, like fermentation, is a long-term social commitment that is constantly evolving and would be at risk of decline if there is no investment in its maintenance and protection.

## Fermentation and the Boundaries of Agriculture

Fermentation activities, by being one of the first agribusiness activities, have expanded the range of activities that define agriculture to go beyond food production to processing of crops in order to produce new materials; some of them serve as nourishment, while others have different purposes. With fermentation, the agricultural system expanded to include wineries and bakeries in addition to field crops and livestock. Now, fermentation is a key to generating biofuels, and biofuel refineries are becoming a part of agribusiness, linking agricultural to the energy sector. The new bio-economy will drastically expand the range of products that originated with agricultural activities to include food, new medicines, and chemicals and thus provide new sources of support to the rural sector to make the rural economy a much bigger part of the major industrial sector. Since the bioeconomy is knowledge intensive and requires significant investment in research and development—both to discover new products as well as to protect against disease—the agricultural sector and the rural regions that will be involved in modern bio-economy activities have to expand their scientific capabilities and we expect to see an inflow of capital, both physical and human, to the life science disciplines that will support the new bioeconomy. This investment in research is likely to forge a link between agricultural related research, engineering, and scientific research. The emergence of organizations like the Energy Biosciences Institute (EBI) at the University of California-Berkeley (which links crop science with basic biology, chemistry, ecology, and industrial engineering, as well as social and decision sciences) are likely to become more of a norm rather than an exception.

## Conclusions

The wide range of economic activities that are built around fermentation provide an illustration of the potential of the new bio-economy. The new bio-economy will be a crucial part of the future of agriculture, both by providing new technologies to improve varieties as well as expanding the range of products that are produced by agriculture. It will lead to a transition to a more sustainable economic system with more reliance on renewable resources and reuse. The new bio-economy will require moving outside of our comfort zone and may require us to take calculated risks, but within a technological framework, we can control and mitigate these risks. The evolution of the new biotechnology, like the fermentation-based technology, will encounter resistance, but its potential is so vast that it is likely to prevail.

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