Vinasse Treatment in Brazil from 1970s to 1990s: a Lock-in Case Study into the Ethanol Agroindustry

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Abstract: Adding market value to a former by-product or waste must be an outcome of what is being called an eco-innovation. Vinasse is an important by-product of sugarcane processing in the manufacture of ethanol in Brazil. Until the 1970s, the main destinations of vinasse were surface waters and sacrifice areas. The fabulous augmentation in production of the effluent after the Pro-Alcool and the legal prohibition of vinasse discharges into rivers and other surface waters induced the exploration of new technological possibilities to its destination. During the two subsequent decades, several technological possibilities were under development. In the middle 80s, fertigation was held as the most diffused alternative and the problem was considered solved. This paper exposes the manifold aspects of the problem and the results of an enquiry into the technological trajectory building process that was guided by public and private decision-making focused on the solution of the problem.

Keywords: Bioethanol. Technological change. Environmental impacts. Environmental regulation. *Lock-in*.

JEL Classification: Q16; Q55; O33.

1 Introduction

Until the 1970s, the main destinations of vinasse or stillage (a by-product of ethanol production) were surface water and the so-called sacrifice areas. With the extraordinary increase in production of the waste after the implementation of the Pro-Alcohol, and with the statutory prohibition on release of vinasse in rivers in the late 70s, efforts were made to develop technological opportunities for its destination.

Over two decades, many technological possibilities were the subject of research and development. During the 1980s, a promising path was the development of the biodigestion, a biotechnological treatment of the waste that produces biogas.

Biogas produced by this biotechnological via failed to succeed in the market place. The mainstream literature concerned to examine the elements that hold

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back the creation and diffusion of cleaner technologies includes top-down and bottom-up arguments (CARRILLO-HERMOSILLA; GONZÁLEZ; KÖNNÖLÄ, 2009). Top-down arguments are mainly developed by economists using aggregate economic models and bottom-up arguments are put forward by engineering studies. These arguments are considered too simplistic in focusing the dynamic of energy substitution and the technological change.

An alternative, evolutionary perspective has been proposed to overcome the shortcomings of the precedent approaches. This perspective explains the difficulties of creation and diffusion of cleaner technologies on the basis of the fact that the economic system can be locked-in to technological standards that are potentially environmentally inferior (CARRILLO-HERMOSILLA; GONZÁLEZ; KÖNNÖLÄ, 2009).

This perspective, which was pioneered by David (1985) and Arthur (1988), is been developed by a number of lock-in studies, in a broad-understood evolutionary approach, mostly in the energy sector (COWAN; KLINE, 1996; JACOBSON; JOHNSON, 2000; UNRUH, 2000; JACOBSON; BERGEK, 2004; FOXON *et al.*, 2005; RAVEN, 2005; VAN DEN BERGH *et al.*, 2006; VERBONG; GEELS, 2006) and in the transport sector (SCHOT *et al.*, 1994; COWAN; HULTEN, 1996; HOOGMA *et al.*, 2002).

Generally speaking, in the view of this literature, lock-in phenomena are due to the existence of significant increasing returns to adoption of existing technologies produced by economies of scale, learning and networks. These economies must be understood by the integration of these technologies into the techno-economic system.

In this paper, we studied the formation of a technological trajectory from public and private decision-making actions taken to solve the problem of disposal of vinasse and the development of new technologies.

For this study, it´s useful to keep in mind the achievements that reveal that cleaner technologies face serious obstacles raised by the existence of increasingly high uptake performance due to the effects of economies of scale, learning and network externalities (ARTHUR, 1988; KEMP; SCHOT; HOOGMA, 1998; DOLFSMA; LEYDESDORFF, 2009). The understanding of these obstacles implies the consideration of the co-evolution of both technological and institutional processes (CARRILLO-HERMOSILLA; GONZÁLEZ; KÖNNÖLÄ, 2009, p. 30-31).

More to the point, conventional economic approaches are being criticized in the view of the fact that the main questions are not optimization and equilibrium but path-dependent technological change within a context of co-evolving environmental, social and economic processes characterized by both irreversibility and uncertainty (LLERENA; MATT, 1999; MULDER; VAN DEN BERGH, 2001; FRENKEN; HEKKERT; GODFROIJ, 2004).

As has been shown by Montalvo (2007), the factors that hinder clean technologies go besides economic ones, including government policy, markets, communities and social pressure, attitudes and social values, technological opportunities and technological capabilities and organizational capabilities. It is been accepted that these factors, which can spur or hold back cleaner technologies, are intertwined as they may affect each other.

We argue that studying the co-evolution of technological and institutional processes in the formation of the technological trajectory requires a historical perspective and the consideration of the constitution of the relevant selection environment. Kemp, Schot and Hoogma (1998, p. 177) note that precedent technologies play a key role in the shaping of the selection environment through the emergence of production routines, infrastructures building, skills and habits formation, and consumption patterns creation.

Along with the recognition of these views, we put forward that the constitution of the relevant selection environment keeps close connections with the scientific understanding of the environmental problem in cause and with the social pressures to solve it.

These are the fundamental reasons raised by the literature for which we particularly discuss here three aspects: the characterization of the problem of vinasse (in its various dimensions: historical, economic, environmental, scientific and social), the relevant selection environment in determining the winning technological trajectory, and the lock-in in fertigation.

The organization of the paper counts with three sections. In the first one, an extensive characterization of the problem of vinasse disposal is carried out, taking into account its distinctive aspects: historical, economic, physical or environmental, social and scientific. The second section presents the analysis of the process of finding new technological solutions, focusing more attention on two competing technological paths: the fertigation and the anaerobic digestion. The third section presents the development of the selection environment that contributed to the establishment of the winning solution. The final discussion identifies the elements which contributed to the stability of the existing option (lock-in) and which constitute obstacles to the success of the alternative one.

2 Characterizing the Vinasse Disposal Problem

In this section, we characterize the environmental problem of the vinasse disposal in its distinctive aspects: historical-economic; physical or environmental; and social and scientific ones.

2.1 Historical and Economic Aspects of Vinasse Disposal

Vinasse – or stillage – is a byproduct of the process of ethanol production from the distillation of fermented juice of sugarcane.

For decades, even while it was not generated in the current volumes, vinasse was a cause of some health and environmental concern by both environmental control agencies and the scientific community in Brazil. The work of Almeida[1] (1955 *apud* SZMRECSÁNYI, 1994), had already shown that the issue aroused the attention of scientists and was subject of studies in the 40s and 50s, the time when the waste was dumped into surface waters and sacrifice areas, two practices that remained in use for a long time.

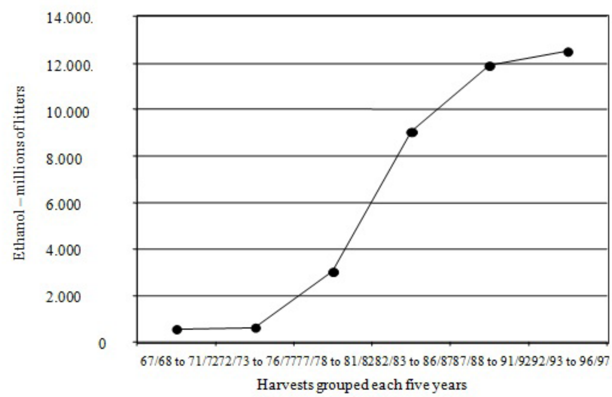
With the implementation of the National Alcohol Program (Pro-Alcool), however, the environmental damage to flora and fauna from surface waters acquired an alarming dimension.

The National Alcohol Program was created, as we know, in order to promote the partial replacement of the gasoline used in light vehicles by hydrated alcohol as part of the actions taken by the Federal Government to reduce the impact of the rising oil prices in the 1970s. (SZMRECSÁNYI, 1979; LA ROVERE, 1981; FURTADO; SCANDIFFIO; CORTEZ, 2011).

Since the mid-70s until the late '80s, the spur to the ethanol production gave new impetus to the sugarcane agribusiness in the country. Figure 1 shows that with the implementation of the Pro-Alcohol, the scale of domestic production of ethanol has raised significantly. From the 638 million gallons per annum, which were produced on average in the first half of the 70s, production increased dramatically at the end of the 90s, with the approximate volume of 16 billion gallons annually. Out of that amount, about 15 billion is of ethanol fuel (SCHELEDER 1998).

1 ALMEIDA, J. R. *O problema da vinhaça*. Rio de Janeiro: Instituto do Açúcar e do Álcool, 1955.

Figure 1 - Brazilian Ethanol Production Trend - annual average volume produced grouped each five years

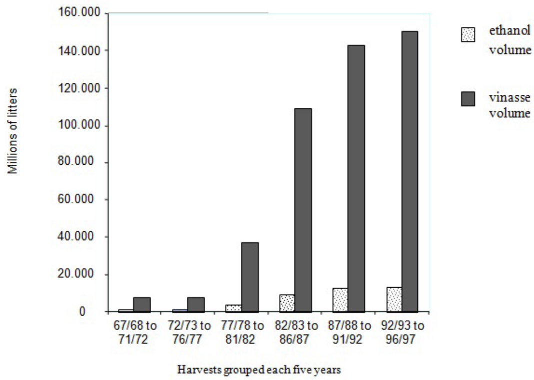


Source: Corazza and Salles-Filho (2000) and Corazza (2001).

The rise of the ethanol production had allowed the national production of alcohol cars to reach 96% in 1985. However, the growing production of ethanol in Brazil has led inevitably to increased production of vinasse, worsening the problem of the waste disposal. As each liter of alcohol generates about 12 liters of vinasse, the growth of production of this waste was dramatic. The volume of vinasse generated annually in the country can be estimated, according to data presented by Hassuda (1989) in view of the production of alcohol at the end of the 90s, something around 192 billion gallons. The data on the path of the generation of vinasse are shown in Figure 2.

It should be noted that while there has been technological improvements in the sugarcane agro-industry since the implementation of ProAlcool, the ratio between the amount of vinasse generated per liter of alcohol showed no significant improvement, except in some plants, making them not only producers of alcohol (and sugar) but also of huge quantities of waste. Probably the fact that the sugar industry had not made significant efforts directed towards reducing the proportion of alcohol and vinasse must be linked, on the one hand, to their heterogeneous nature and, secondly, to the lack of a more restrictive environmental regulations. Later on, the establishment of fertigation as the winning solution will surely explain this lack of effort.

Figure 2 – Brazilian ethanol and vinasse production trends from 1967 a 1997. Averages were calculated in million of liters for harvests grouped each five years



Source: Corazza and Salles-Filho (2000) and Corazza (2001).

Interestingly, back in the 80's when National Alcohol Program was under a crisis, the environmental issue has tended to become an argument in favor of the program, such as was the case of the national energy independence issue in the early years of its implementation. Authors such as Cortez and Larson (1998), describing the environmental impacts of ethanol production, were enthusiastic about its advantages: the positive balance of CO2, the power generation from a renewable source and the possibility of producing electricity through cogeneration plants.

For reasons like these, World Commission on Environment and Development has quoted ProAlcool in its famous book Our Common Future as a good example of renewable energy source exploitation.

If ProAlcool finds reasons to favor its continuity on environmental grounds listed by many authors, there are also those not so happy with other environmental impacts of the Program. Many authors, such as La Rovere (1981), Margulis (1982), Guarnieri and Januzzi (1992) and Szmrecsányi (1994), indicated negative impacts of the Program on environmental quality, particularly concerning vinasse disposal.

2.2 Physical and Environmental Aspects of Vinasse and its Disposal

Vinasse is an effluent rich in organic matter and potassium, with significant levels of calcium, magnesium and sulfur and other minerals in small quantities. This is, in accordance with Plaza Pinto (1999), a substance of suspended organic solids and minerals with high COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand), which explains its great pollution potential.

Along with pollution from organic substances, other physical aspects of vinasse are its low pH and the high temperature in which it is generated, resulting in its character of chemical pollutant (expressed by a high corrosion) and pollution of the physical nature (in the form of heat).

When it comes to the origin of the effluent, the sources are identifiable because they correspond to plants producing ethanol in the sugarcane agro-industry. As for the use of vinasse, the main sources are in sugarcane production, corresponding to multiple properties of planters. There is no survey on the amount of vinasse used in these properties annually, making it difficult to accurately identify those sources. In Sao Paulo, for example, the axis Campinas - Ribeirão Preto concentrates most of these rural properties.

The elements of the ecosystem that are potentially affected are surface water, soil and groundwater.

By the end of 70s, increasing volumes of vinasse were released into surface waters. The proliferation of microorganisms due to exhaust the oxygen dissolved in water causes the destruction of aquatic flora and fauna and hampers the supply of drinking water. Besides the stench, Almeida[2] (1955 *apud* SZMRECSÁNYI, 1994) called attention to the worsening of endemic diseases such as malaria, amoebiasis and schistosomiasis.

The release of vinasse into surface waters were seasonal, following the cycle of ethanol production, which explains the acute nature of the problem, affecting the functions of self-regulation and self-reproduction of ecosystems. After the shock, along with the dilution of pollutants, fish populations seem to recover.

Another alternative for disposal of the vinasse is the so-called sacrifice areas, surface areas that receive or are flooded with the untreated vinasse. Evidently, the sacrifice areas become useless for any other purposes.

Later, particularly from the 80s, with the spread of the practice of fertigation, which is going to be detailed later in this paper, and with the still continued use of sacrifice areas, soil is the element of ecosystem that becomes the more affected by vinasse disposal.

Finally, we discuss, as we shall see, the possibility of contamination of groundwater sources. Given the controversial nature of this discussion, it will appear below.

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2 ALMEIDA, J. R. *O problema da vinhaça*. Rio de Janeiro: Instituto do Açúcar e do Álcool, 1955.

2.3 Socio-scientific Controversies of the Vinasse Disposal

While the effects of the discharge of vinasse on the water surface are well known to the point to raise no more disputes, the same does not seem to occur with the environmental impacts of their disposal into the soil or with the possibility of contamination of groundwater.

There are a number of scientific papers devoted to studying the effects of vinasse as fertilizer, while few research initiatives are turning to the effects of the waste on groundwater quality.

We have observed that, according to studies of Gloria 1984 (*quoted* by Plaza Pinto, 1999), the failure to observe the optimal doses of vinasse (which vary according to soil type and to the sugarcane varieties), leads to risk of salinization and degradation of the very quality of sugarcane produced. Despite this and although the wide diffusion of fertigation, Copersucar released in 1986, according to Plaza Pinto (1999), the information that about 40% of the vinasse produced in the State of Sao Paulo is not yet exploited. This amount is discarded into sacrifice areas, a practice that has been authorized with restrictions by the Company of Technology and Environmental Sanitation (Cetesb), which requires the use of waterproof blankets of PVC to cover the soil of these areas, for the protection of groundwater and surface waters. Given that the alcohol industry is a factor of aquifers vulnerability, this high percentage may be considered critical. Hirata *et al*. (1991) show that the region that concentrates most of the sugar and alcohol production in the State of São Paulo (axis Campinas - Ribeirão Preto) is located exactly on the recharge area of the Guarani Aquifer, one of the most important in South America. In this area, the groundwater is relatively close to the surface, which makes it vulnerable to infiltration of pollutants, especially the salts (potassium, nitrates, etc.). For this reason, Hassuda (1989), Cruz (1991), Righetto, Cruz and Nogueira (1991) and Gloeden *et al*. (1991) developed methods for monitoring the risk of groundwater contamination by leakage of vinasse and conducted studies on the possibility of contamination of groundwater aquifer belonging to the so-called Botucatu Aquifer (the region of the Guarani aquifer recharge). Although no contamination was found at the time, the results of these studies indicate leaching of nutrients from the vinasse into the groundwater, especially nitrates. For this reason, the authors reiterated the danger of further degradation of aquifers and were unanimous in stressing the need for more research on the risks of infiltration of vinasse into soil / fertigation for groundwater quality and human health.

It is appropriate to note the existence of the argument that the very cultivation of sugarcane would be responsible for absorbing very quickly most of the salts (especially potassium), and therefore prevent both the risk of salinity as well as that of contamination of groundwater. However, given the total absence of control over the fertigation, it is not possible to confirm the validity of this argument.

Thus, there is controversy about soil salinization and underground aquifers contamination. The possible causal chains between the use of vinasse into the soil, and the size, scope and timing of the appearance of adverse effects remain unclear.

It appears that the frequency and intensity of the release of vinasse into soil can influence the possibility of salts (potassium, nitrates, etc.) accumulation, producing, eventually, both effects: salinization and groundwater contamination. These gloomy possibilities clearly demand more research and scientific discussion. However, at least so far, these issues seem to be doomed to oblivion.

3 Technological Developments in the 1970s and 1980s

As pointed out by Margulis (1982), ProAlcool was not preceded by a stage of research with specific and coordinated programs in order to optimize production processes or to minimize waste and maximize materials recovery. It was only after the establishment of its ambitious targets for increasing the production of alcohol (and vinasse), that several research centers have turned to the study of the problem of vinasse disposal. Thus, only when the immense amount of the waste (generated with the expansion of ethanol production after ProAlcool) showed the extent of the problem of its disposal, that efforts have been mobilized to develop technological possibilities to its solution. These possibilities included aerobiosis, recycling of the effluent in the fermentation process, the fertigation, the combustion, the production of yeast, the use in construction, the manufacture of animal feed and anaerobic digestion.

Aerobiosis, recycling in fermentation and fertigation are simpler solutions from the technological standpoint, and sugarcane agro-industry had already some knowledge of them. These alternatives benefited also of some diffusion. It is likely that the low technological sophistication of these processes has made possible its use in industrial scale within the first years of ProAlcool.

Combustion, the production of yeast, the use of vinasse in civil construction and in the manufacture of animal feed, as well as the anaerobic digestion, were under differentiated stages of development, each in different degrees of maturity and intensity of research. It is possible that technological sophistication of these solutions had represented an obstacle to its dissemination within a sector traditionally of low technological dynamics.

In the next section, we discuss the main advantages and problem areas faced by each of these alternatives, during their specific technological development efforts. Further, we describe and analyze the two alternatives that have gained more strength: the fertigation in terms of dissemination of its adoption, and anaerobic digestion, because it has mobilized expertise and institutions and provided a bet on the emergence of biotechnology as a new technological paradigm.

The study of such technologies allows their classification into four groups according to the type of the waste treatment needed: 1) technologies that require concentration of the residue by evaporation, 2) aerobic fermentation, 3) anaerobic digestion, and 4) other uses for untreated vinasse.

The creation of new skills and the mobilization of different institutions behind these tracks or technological trajectories allows us to speak, to use the words of Dosi (1982), of a period of extraordinary search, or a pre-paradigmatic phase. We are able to speak also of the emergence of capabilities in the technological domain as well as in the organizational field, two fundamental factors pointed by Montalvo (2007) affecting cleaner technologies.

4 The Relevant Selection Environment Definition

We feature here the relevant selection environment to the formation of the technological trajectory to solve the problem of disposal of vinasse.

The selection environment has to do with Carrillo-Hermosilla, González and Könnölä (2009) institutional environment that includes public policies, laws and organizations. While these aspects are taken into account here, we go further the authors´ proposal to characterize the selection environment by briefly characterizing three points. a) The technological aspects of the industry structure. b) A key macroeconomic element affecting the formation of the technological trajectory, as to say, oil prices, since petroleum is the main substitute energy source for ethanol. And, c) a specific aspect of the institutional environment which consists of the level of institutionalization of the biotechnology at the time.

As we have already pointed out in this paper, the constitution of the relevant selection environment keeps close connections with the scientific understanding of the environmental problem in cause and with the social pressures to solve it, aspects developed in the previous sections. Here we try to shed some light on the connections of these aspects and the constitution of the selection environment.

In the alcohol sector, the agricultural and industrial phases do not always correspond to the same unit of venture. Thus, with regard to market structure, it is interesting to distinguish between two types of structure elements: the first is linked to units at the origin of the residue, while the second is related to units that uses the vinasse generated by the former ones. The first type of market structure involves the distilleries (which may be autonomous, while only producing alcohol, or attached, when they produce sugar and ethanol). The second type involves the planters and therefore users of fertigation. Taking into account this distinction, it is possible to say that the industry has become more concentrated in the first and more sprayed in the second type.

With regard to the distilleries, we point out the technological duality between autonomous and attached distilleries. Different manufacturing processes make vinasse produced by independent (autonomous) distilleries more concentrated in pollutant load than that produced in attached distilleries: that is, the production of ethanol directly from the fermentation (in autonomous plants) generate more vinasse than indirect production from the fermentation of diluted molasses (in attached plants). With ProAlcool, since 1975 most of the plants was conceived as autonomous, because it was not aimed to produce sugar, but ethanol. Consequently, most ethanol plants operating in the country are autonomous - that is, the type in which there is a larger ratio vinasse/ethanol. What is important to point out, however, is that for the industry as a whole successive crisis have taken place over the 1990s (with a reduction in ethanol prices, a drastic reduction in the production of ethanol fueled cars, the lack of a policy for the sector), leading to the cooling of the investment capacity of the sector. We consider this a factor that favored the adoption of technological alternatives for the less innovative destination of vinasse.

The elements of the macroeconomic environment that influenced this selection can be identified with low oil prices that have prevailed in those years. Low oil prices in the second half of 1980s reduced the competitiveness not only of ethanol but also made it difficult to expect economic pay-off from vinasse's biogas.

Recently, brand price volatility proceeds as instable macroeconomic signs adding more uncertainty to the private investment horizon. Investment in biogas recovery from vinasse treatment, as mentioned above, is of great importance for economic viability of anaerobic digestion. In this paper, we design a whole set of analytical categories to study the vinasse disposal problem that should help to alert the reader that the conformation of a technological trajectory is not in any way, single-determined. Oil prices, in this sense, represent only one aspect that contributes to this multi-determined phenomenon. As we see, persistently low prices of oil (and, in the case, especially diesel - also explained by the existence of fuel subsidies in the country - which is one element of a political legal-institutional nature) make higher the opportunity costs of investments in alternative energy technologies (such as biogas).

Elements of a political-legal and institutional environment that characterize the relevant selection environment for an alternative to fertigation include regulation on vinasse disposal and weak institutionalization of biotechnological research.

From the standpoint of the rules on vinasse disposal, as can be seen in Table 1, from the 78/79 crop it was forbidden to dump waste into surface waters, non compliance being punished with a fine.

Table 1 – Trend in regulation affecting vinasse disposal

Legislation	**Description**
Ordinance of the Ministry of Interior n° 323 29/11/1978	Ban vinasse disposal (direct and indirectly) into surface waters. Require distilleries to present projects for the implementation of systems to vinasse treatment or use.
Ordinance of the Ministry of Interior no 158 November, 1980	Broadens the former Ordinance to the rest of the residual waters e liquid effluents from distilleries, and establishes deadlines and legal procedures for compliance projects elaboration and implementation. Restricts the access to government funding and incentives to the existence and approval of such projects.
CONAMA Resolution n° 0002 05/06/1984	Make it compulsory the presentation of studies and of a project with the solution to control the pollution caused by the effluents from distilleries and by sugarcane wash waters.
CONAMA Resolution n° 0001 23/01/1986	Make it compulsory the Environmental Impact Assessment and its respective Report for new distilleries and for any expansion projects for the existent ones.
Act n° 6.134 02/06/1988, art. 5°, Sao Paulo State Government	Establishes that liquid effluents, solid wastes and gases from any agro-industrial, industrial, commercial or other in nature, only can be disposed in forms that do not pose risks to groundwater.
CETESB Technical Standard 4.231 March, 2005	Establishes criteria and procedures for application of vinasse into the soil, in the State of São Paulo.

Source: Authors´ elaboration.

The relevance of this legal ban seems clear. Margulis (1982) considers that fertigation has become an effectively diffused practice for biofuel industry by the time of the 1979/80 harvest, immediately after the release of the ban of vinasse disposal into surface waters.

Hassuda (1989) points out that the State of Sao Paulo counts with legislation on the aquifer contamination since 1988 and that, so far, there were not any acts in the Federal level about the theme. Actions in this domain only were taken in 1999.

Rebouças (2002) calls attention to the fact that the project of the federal act to the regulation and management of groundwater (nº 7.127/86), had been under negotiation in the Parliament for over a decade, its promulgation being necessary to the regulation of Act 9.433 which involves water resources in general and promotes practical aspects for groundwater management.

Adopting an integrated policy to water resources (surface and groundwater) is a compromise that Brazil assumed in Agenda 21.

With regard to biotechnology, the initiative of major significance for the institutionalization of research in this area corresponds to the National Biotechnology (PRONAB) of the Department of Planning/National Research Council (SEPLAN/CNPq), in 1982.

Salles-Filho, Cerantola and Alvares (1985, p. 23) comment on the PRONAB:

> Despite the policy initiative that was launched, little was made of what was intended, since the unfavorable political and economic determinants that severely diminished the resources for Science and Technology development in the country.

PRONAB intended, through its extension in the State of Sao Paulo - the State Program for Biotechnology, to implement a series of actions to the development of anaerobic digestion (Anaerobic Digestion Sub-Program). Among its short-term priorities, the Anaerobic Digestion Sub-Program focused on basic and technological studies on anaerobic digestion of sewage from the sugar and ethanol mills - as well as urban waste and sewage. To cope with these aims, the Sub-Program would have funded projects aiming at integrating knowledge from microbiology and process biochemistry, anaerobic digesters optimization - more efficient from a technical-economic standpoint, granulation study in upflow digesters, evaluation of building materials, consideration of the application of biogas and biofertilizer, spur of projects of deployment and diffusion of the developed technologies. This sub-program was not effectively implemented.

As previously mentioned, the existence of subsidies for diesel also constitutes a political and legal element to be considered, for it helps to boost the opportunity costs of alternative energy investments.

As regards to the elements of the natural environment, it is possible to say that just as the existence of watercourses in the neighborhood of plants and distilleries has long favored the practice of vinasse disposal into these waters, the availability of abundant land has also favored its view as a natural disposal for vinasse.

As elements of a social problem involved in the vinasse disposal, Plaza Pinto (1999) refers to episodes of disputes involving plant owners and the public because of the discharge of the distillery effluents by the formers into the surface waters, with serious problems of local pollution. In his work of 1984, Rezende[3] (1984 *apud* PLAZA PINTO, 1999) reports ten major cases of contamination with vinasse published in the national press between 1943 and 1984. All episodes reported local catastrophes, such as large fish kills, water shortages, excessive proliferation of insects, public health problems and disruption of local economies dependent on fishing. One of the cases occurred in 1984, between the dams of Sobradinho and Moxotó in San Francisco River, was caused by the rupture of a stillage dam resulting in the spill of 45 billion m3 of vinasse in Tourão Creek, a tributary of San Francisco by Agrovale company. The result became known as the largest ecological disaster in the San Francisco River, killing 300 tons of fish. Although Agrovale tried to conceal the evidence of contamination, turning the land contaminated the river with tractors, it failed to dissuade the public and the authorities of its responsibility. According to author's account, the revolt of the river dwellers, whose survival depended on fishing, gave prominence to the episode. The option for fertigation, which reduces the risk of contamination of water supplies in the short term, certainly has been helped by episodes like this, involving accidents caused by disruption of vinasse tanks leading to spillage of waste into surface waters.

5 Final Discussion: Understanding Lock-in by Multi-determined Events

This paper presents the main results of a research focused on the analysis of the multiple factors involved in the formation of a technological trajectory for the solution of the vinasse destination problem in Brazil in the period of the 1970s to the 1990s.

We share a broader evolutionary view that cleaner technologies may be hold back by obstacles that must be understood by considering, above and beyond the essentially economic or technical factors – the top-down and the bottom-up approaches identified by Carrillo-Hermosilla, González and Könnölä (2009), the co-evolution of the change processes, both technological and institutional. Besides, along with Llerena and Matt (1999), Mulder and Van Den Bergh (2001) and Frenken, Hekkert and Godfroij (2004), we embrace the notion that it is essential to focus on path-dependent technological change within a context of co-evolving environmental, social and economic processes characterized both by irreversibility and uncertainty, rather than on maximization and equilibrium, emphasized by mainstream economics.

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3 REZENDE, J. O. Vinhaça: outra grande ameaça ao meio ambiente. *Revista Magistra*, v. 1, p. 34-148, jun. 1984.

This approach must prevent us to say that the ultimate reason that explains why fertigation came to be the winning solution to the vinasse disposal problem could be its cost-effectiveness. This result could be achieved by means of a conventional cost-benefit analysis. Studying the economic feasibility of alternatives at the time, Margulis (1982) was enthusiastic about fertigation, but did not rule out the possibility that, over time, anaerobic digestion – still immature from technical point of view – could came to be an economically viable option.

After almost thirty years from the Margulis' evaluation, fertigation remains the most widespread solution in the country, and have been consolidated in practice as the solution to the vinasse disposal problem.

Van Lente (1997) found that biotechnology had gained widespread attention by the promise of helping to reduce pollution and to provide energy production, opening up new perspectives to contribute to sustainable development and the process of the greening of industry. These possibilities could characterize the technological opportunities, as refereed by Montalvo (2007), and could also be understood as a business opportunity. During two decades, comprising the years of 70s and 80s, anaerobic digestion brightly represented a possibility for this promise to be fulfilled in Brazil.

It is clear that the promises of biotechnology were not restricted to Brazil or to a specific industry. The widespread belief in the emergence of a new paradigm that could replace the old chemical pathways for the production of pharmaceuticals, agrochemicals and a wide range of new products impacting across major industrial sectors were supported, as indicated by Van Lente (1997) by undeniable evidence: significant scientific developments, the reduction of the gap between basic and applied science, the climb of incentives for equipment development, the magnitude of inter-sectoral impacts forecasted. Would these be evidence of an overly optimistic prognosis with respect to the development of biotechnology and its applications, as in the case of anaerobic digestion?

By that time (late 1990s) and in the specific case of vinasse biodigestion, the gap between the promise of biotechnology and their actual achievements is directly proportional to the general disappointment after the euphoria experienced in the early 80s.

In our particular case study, we list a number of elements that help us not to confine our understanding of the upholding of fertigation as the resolution to vinasse problem to a too simplistic cost-benefit explanation. In the paragraphs below, we point out elements that contribute to the continuity of the technological trajectory of fertigation and the exclusion of alternative anaerobic digestion. We also advance a few comments on the possibility of breaking the consolidated trajectory.

Initially, it would be logical to assume that a cost-benefit analysis, even if not formalized by the users, had been largely in favor of fertigation, along with its high cost-efficiency. The work of Margulis (1982) is illuminating on these points.

As it was already pointed out, the sugarcane agro-industry, with traditionally simple technology, is not characterized by a significant technological dynamics: let us remember, once more, the proportion of generation vinasse and ethanol remained practically unchanged since 1975 despite the investments offered by ProAlcool. Probably the manufacture side of the sector could be best described, by the time, by organizational rigidity and resistance to innovation, which is mostly dependent of suppliers.

The same is not true, nevertheless, when it comes to the innovative efforts that are traditionally by a web of mainly, but not exclusively, public supported agents. These agents are related to the sugarcane industry in the domain of genetic improvement of the plant, combating pests, agricultural and harvesting techniques, impact of the cultivation on the environment, and, more recently, technologies concerning the manufacture of ethanol, including hydrolysis and fermentation (FURTADO, SCANDIFFIO and CORTEZ, 2011; SALLES-FILHO; BONACELLI, 2010; THE STATE OF SÃO PAULO RESEARCH FOUNDATION, 2007; SALLES-FILHO *et al*., 2000).

The urgency to give a destination (an alternative to surface water) to huge amounts of vinasse within extremely tight deadlines - implemented by Ordinance of the Ministry of Interior in 1978-79 – appears to have benefited fertigation; it can be said that this was the most accommodating alternative to the selection environment at the time.

The developments experienced by fertigation through the 70s and 80s provided the technological trajectory the exploitation of economies of scale, in the way discussed by many authors (DAVID, 1985; ARTHUR, 1988), but also of the economies of scope. In terms of scale, the development of dispensing systems has expanded the acreage that could receive the waste in an economically efficient way. In terms of scope, the study of rates of disposal has made possible the substitution of the waste for chemical inputs (fertilizer).

We also believe that one can talk, to a certain degree, of technological interdependence (between fertigation itself and the application technology and infrastructure) to the extent that widespread use of fertigation just followed the ban on the release of the waste into surface waters, i.e. from the 1979/80 harvest. This possibility is reinforced by the need for closer links between users (producers of sugarcane) and suppliers of fertigation equipment. This observation is consistent with the notion of system integration of the technological solution put forward by authors like Kemp, Schot and Hoogma (1998). The narrowing of these links tends to favor the qualification of users in the operation of such equipment and the establishment of a certain infrastructure (canals or pipelines, investments in trucks, tanks and pumps etc.), which contributes to strengthen the advancement of the technological trajectory, as was already pointed out by David (1985) and Arthur (1988).

The achievement of these investments, on the other hand, implies the emergence of sunk costs. Although it is difficult to specify precisely the dimension of these costs, one can say that their importance tends to be greater when considering the crisis faced by the sector at the time, characterized by the stability of the selection environment (with diminishing demand for ethanol as fuel for vehicles and without further pressures for technological change in this area).

The spread of fertigation should also have caused the emergence of some positive network externalities and this observation is in accordance with David (1985) and Arthur (1988). That is to say, the adoption of the application of natural vinasse into soil for the first producers may have performed as a demonstration effect, influencing other producers to adopt it as well.

One could even speak of a lack of information on alternative technologies or of a lack of knowledge about how to use this information, as it is been considered by Carrillo-Hermosilla, González and Könnölä (2009).

In any case, a technology in its initial stages of development, as was the case of anaerobic digestion, requires an extremely low degree of risk aversion from early adopters and/or an expressive expected pay-off. Additionally, in the specific case of this technology, it should require a very great believe in the promising biotechnology paradigm. Indeed, it would be surprising a surge on its adoption in those years. These conditions, namely the low degree of risk aversion and the great believe in biotechnology, seemed to be found only in a few plants in Brazil at the time: PAISA , São Martinho and Boa Vista.

As we saw in the case of development of anaerobic digestion, it is not true that technological opportunities have been opened by new scientific knowledge. It was necessary for researchers to engage to answer questions more properly scientific, while seeking technical solutions to the trade-offs faced.

The expectations on technology change, or on the ability to achieve the promises of biotechnology, however, were strong enough to justify these efforts or support of the bets.

One might think, still, the possibility of coexistence between the anaerobic digestion of vinasse and the fertigation. Perhaps both could, to some extent, be considered complementary rather than properly competing.

The adoption by a small number of plants can be considered as indicative of the possibility of creating certain market niches in which penetration of innovation meet less resistance. The use of biogas for dry yeast can be understood as an attempt to exploit a market niche, which is in accord with the prospects of several analysis (RAVEN, 2005; VERBONG; GEELS, 2006).

The efforts of anaerobic digestion told, in this sense, the willingness of established plants (PAISA, São Martinho and Boa Vista) to engage in innovation and proactive strategy to internalize the treatment of vinasse with biogas production. Nevertheless, we also see the entry of at least one new firm, Biometano, as a supplier of technological capabilities.

Those proved not be sufficient conditions to break the pattern of technological solution that was already spreading (the fertigation).

The main technological bottlenecks faced by fertigation were being overcome in a fairly efficient way. One could not identify any new significant problem area challenging its advance, so that, after having surpassed some technical difficulties, not only fertigation has not faced any economic restrictions but, moreover, has provided a simple, cheap and profitable way to discard huge quantities of the polluting waste. A real Columbus' egg.

The changes that have taken place in the selection environment proved, on one hand, to be favorable to the fertigation trajectory (through the tight deadlines for the compliance with new environmental regulation) and, on the other hand, hostile to anaerobic digestion (due to the weak institutionalization of biotechnology research in the country).

Currently, the disposal of the waste is taken as a solved problem. The main change in the selection environment lies in a localized institution of some criteria and procedures to guide vinasse infiltration into the soil. As pointed out by Mutton, Rossetto and Mutton (2010), there has been local improvement in São Paulo State legislation to establish criteria and procedures to vinasse infiltration, taking into account the physical characteristics of the soil. Besides, it is not necessary here to retrieve all the advantages attributed to fertigation.

It is undeniable that fertigation has constituted an extremely effective response when compared to vinasse release into rivers. The effects of this practice were sufficiently obvious not to raise scientific disputes and to justify the tightness of deadlines to compliance.

However, that certainty with respect to environmental impacts of the release of vinasse into surface waters is unlikely to be repeated, as we have already pointed out, in the case of the potential environmental effects of its disposal on the ground.

We saw that the ethanol agro-industry activities have been identified as one of the vulnerability factors of Sao Paulo aquifers and some studies have called attention to the risk of groundwater contamination by vinasse disposal into the soil. Soil salinization is also identified as a danger associated with this practice.

Both the groundwater contamination and soil salinization are treated as risks and the few studies available on the matter are still inconclusive. Given these risks, there remains the question if the fertigation would not only be a temporary, short-term solution given the emergency of the vinasse disposal problem. It seems, likewise, that it was premature to abandon efforts to develop the anaerobic digestion of the waste.

What is clear is that more research was needed to clarify those questions. In the absence of such a clarification, we are left with the impression that we are dealing with a case where the solution retained is a quick and inexpensive way to get rid of the sugarcane agro-industry annoying and perhaps even dangerous waste. Worse than that, not to investigate these issues implies leaving to future generations the task of discovering whether the infiltration of vinasse into soil actually contributes – or have contributed – to soil salinization and groundwater contamination.

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Recebido em: 21/06/2011.
Aceito em: 15/01/2014.