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Water, wastewater and waste management in brewing industries

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Abstract

Water and wastewater management constitutes a practical problem for the food and beverage industry including the brewing industry. In spite of significant improvement over the last 20 years, water consumption and disposal remain critical from an environmental and economic standpoint. This paper gives an overview of the world beer market in order to highlight the heterogeneity in capacity of global beer production. From a synthesis of existing literature, water consumption is analysed and the most common treatments and the associated costs are reported. Finally, biological and technical alternatives including membrane operation processes and economic reality are described.

Keywords: Breweries; Water; Waste management; Technical alternative; Membrane process

1. Introduction: overview of world brewing industry

In the food industry, the brewing sector holds a strategic economic position with the annual world beer production exceeding 1.34 billion hectolitres in 2002 [1]. Beer is the fifth most consumed beverage in the world behind tea, carbonates, milk and coffee and it continues to be a popular drink with an average consumption of 23 litres/person per year. The brewing industry has an ancient tradition and is still a dynamic sector open to new developments in technology and scientific progress. However, this market hides an important heterogeneity of production capacity [2,3]; for example in 2002, the world's 10 largest brewing groups shared almost 50% of the world production (production capacity superior to 100 million hl/year for Anheuser-Bush and Interbrew groups) as shown in Table 1. In contrast, a microbrewery may start its activity with an annual production close to 1000 hl [4].

Brewers are very concerned that the techniques they use are the best in terms of product quality and cost effectiveness. During production, beer alternately goes through three chemical and biochemical reactions (mashing, boiling, fermentation and maturation) and three solid–liquid separations (wort separation, wort clarification and rough beer clarification) [5]. Consequently water consumption, wastewater and solid–liquid separation constitute real economic opportunities for improvements in brewing.

This paper is designed to highlight the emerging and existing constraints in relation to water and waste management in the brewing industry. The most common

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Table 1
Beer production and the world's 10 largest brewing group in 2002 (MS, market share)

Area	Production (10^6 hl)	World's 10 largest brewing group	Production (10^6 hl)	MS (%)
America	457	Anheuser-Bush (USA)	155	11.7
with USA	233	Interbrew (BEL)	90	6.8
Brazil	69	Heineken (NTL)	88	6.7
Mexico	55	Ambev (BRA)	63	4.8
Europe	475	SAB (SA)	60	4.5
with Germany	110	Carlsberg (DAN)	54	4.1
Russia	65	Miller (USA)	52	3.9
UK	55	Scottish & Newcastle (UK)	37	2.8
Asia	337	Modelo (MEX)	36	2.7
with China	230	Kirin (JAP)	35	2.6
Japan	43	Total (World)	670	50.7
South Korea	18			
Africa	48			
with South Africa	11			
Oceania	22			
with Australia	18			
World	1339			

treatment and the associated costs are reported and we present possible biological and technical alternatives to reduce the water consumption and waste production. Membrane processes are detailed as they may provide an alternative to the conventional dead-end filtration with filter-aids as well as a way to reduce water consumption.

2. Water and waste management

Water management and waste disposal have become a significant cost factor and an important aspect in the running of a brewery operation [6,7]. Every brewery tries to keep waste disposal costs low whereas the legislation imposed for waste disposal by the authorities becomes more stringent [8]. Water consumption in a brewery is not only an economic parameter but also a tool to determine its process performance in comparison with other breweries [5–7]. Furthermore, the position of beer as a natural product leads the brewers to pay attention to their marketing image and to take waste treatment (wastewater, spent grains, Kieselguhr sludge, yeast surplus) into account as shown in Fig. 1.

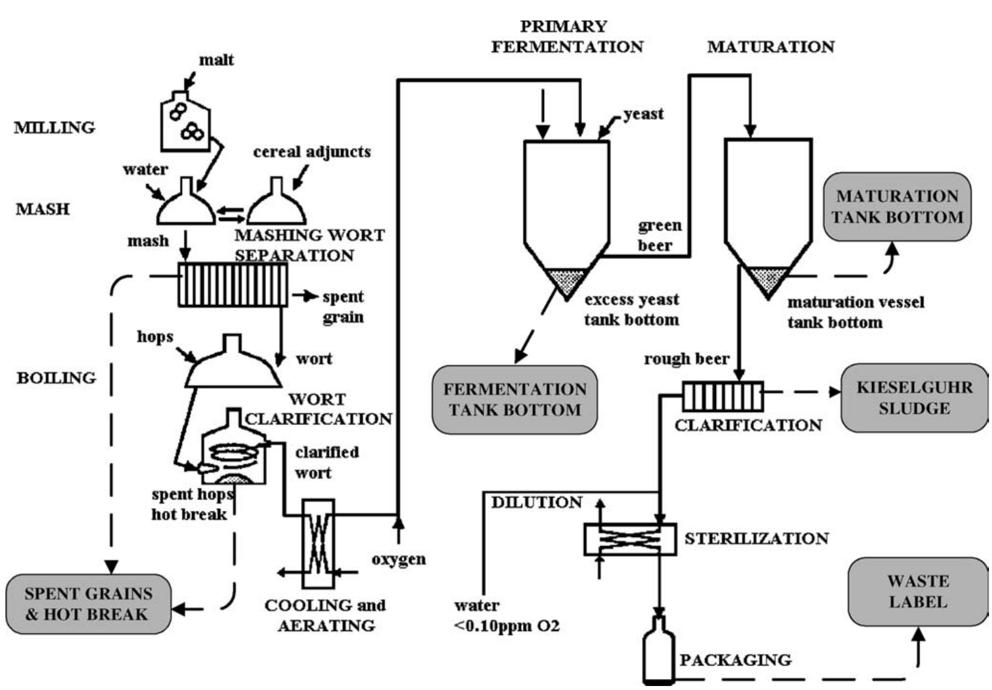

Fig. 1. Brewing process and main waste.

Several legal requirements carry weight in decisions in the beverage industry:

- For industrial waste, the severity of waste management requirements in beverage industry (including brewing) has been increased in Europe in recent years. The consequences are an increasing cost factor due to treatment or dumping. In brewing, diatomaceous earth (Kieselguhr) is increasingly scrutinised because legislation about dumping has come into effect since 2002. In Germany, legislation will be reinforced in 2005 by a technical regulation related to domestic waste and material recycling law.
- From a public health point, the use of Kieselguhr sludge with spent grain as livestock feed is not a durable solution.
- In terms of water management, strict legislation favours a reduction of water consumption and wastewater production in order to reduce the volume to treat.

2.1. Water in the brewing process

The food and beverage processes including brewing are water consuming. Breweries have a specific consumption of water ranging from 4 to 11 hl water/hl beer. In brewing, the average water consumption of around 5–6 hl/hl beer is correlated to beer production for industrial breweries [7]. Water consumption is divided into 2/3 used in the process and 1/3 in the cleaning operations [5].

In the same way, effluent to beer ratio is correlated to beer production. It has been shown that the effluent load is very similar to the water load since none of this water is used to brew beer and most of it ends up as effluent [7].

$$\frac{\text{Water}}{\text{Beer}} = 2.89 + \frac{87\,312}{\text{Beer}}$$

$$\frac{\text{Effluent}}{\text{Beer}} = 2.21 + \frac{545\,892}{\text{Beer}}$$

For $300\,000 < \text{beer} < 600\,000$ hl/month; beer (hl/month) with effluent/beer and water/beer (hl/hl beer)

2.2. Waste and waste treatment

A recent study in German breweries [8] states that spent grains, Kieselguhr sludge, yeast surplus and waste labels represent the major wastes. We describe hereafter those wastes, their volume, the most common treatments Table 2 as well as the estimated cost.

2.2.1. Spent grains

The mashing process is one of the initial operations in brewery, rendering the malt and cereal grain content soluble in water. After extraction, the spent grains and wort (water with extracted matter) are called mash and need to be separated. The amount of solid in the mash is typically 25–30%. At present, spent grains (often mixed with yeast surplus and cold break (trub separation after cooling of wort)) are sold as livestock feed with an average profit close to 5 €/ton (min, 1 €/ton; max, 6 €/ton).

2.2.2. Kieselguhr sludge

Diatomaceous earth has various advantages for filtration in brewing process as reported by Baimel et al. [9]. The conventional dead-end filtration with filter-aids (Kieselguhr) has been the standard industrial practice for more than 100 years and will be increasingly scrutinised from economic, environmental and technical standpoints in the coming century [8,10]. Approximately two thirds of the diatomaceous earth production is used in the beverage industry (beer, wine, fruit juice and liqueurs). The conventional dead-end filtration with filter-aids consumes a large quantity of diatomaceous earth (1–2 g/l of clarified beer) and carries serious environmental, sanitary and economical implications [11]. At the end of the separation process, diatomaceous earth sludge (containing water and organic substances) has more than tripled in weight. From the environmental point of view, the diatomaceous earth is recovered from open-pit mines and constitutes a natural and finite resource. After use, recovery, recycling and disposal of Kieselguhr (after filtration) are a major difficulty due to their polluting effect. From the health perspective, the used diatomaceous earth is classified as 'hazardous waste' before and after filtration (The World Health Organization defines the crystalline silica as a cause of lung disease) and its use requires ensuring safe working conditions. From an economic standpoint, the diatomaceous earth consumption and sludge disposal generate the main cost of the filtration process. In Europe, the economic aspect is strengthened because its consumption is higher (around 1.7 g/l of clarified beer). The disposal routes of Kieselguhr sludge are into agriculture and recycling with an average cost of 170 €/ton. Disposal costs vary widely from one brewery to another with a positive income of 7.5 €/ton up to a maximum charge of 1100 €/ton of Kieselguhr purchased.

2.2.3. Yeast surplus

Maturation and fermentation tank bottoms constitute another source of sludge. Low fermentation beer is produced through two fermentation steps, the primary fermentation being when 90% of the fermentable matter is consumed. A rapid cooling of the tank stops this fermentation and causes the flocculation of insoluble

Table 2
Disposal situation for brewery waste [8]

Spent grains (brewing)	Yeast surplus (tank bottom)	Kieselguhr sludge (clarification)	Waste labels
Livestock feed	Livestock feed	Spread on agriculture ground	
Composting		Composting	Composting
		Chemical and thermal regeneration	Recycling
Drying and incineration			Incineration
Dumping		Dumping	Dumping
Anaerobic fermentation		Raw material in industry (building material).	

particles and the sedimentation of yeast. The tank bottom becomes full of yeast and "green beer". At present, the fermentation tank bottom generates a beer loss of around 1–2% of production [12,13].

In brewing, surplus yeast is recovered by natural sedimentation at the end of the second fermentation and maturation. Commercial sale of this yeast can be made to the animal feed industry. This brewing by-product has dry matter content close to 10% w/w and generates beer losses (or waste) of between 1.5 and 3% of the total volume of produced beer.

2.2.4. Waste label

Waste label disposal is related to product decoration and design and the waste label mass fluctuates greatly. On average, a weight of 282 kg/1000 hl of produced beer has been calculated. Waste labels should be avoided or at least limited since they are not simple papers but wet-strength paper impregnated with caustic solution. The average disposal cost is 38 €/ton (min, 0; max, 92 €/ton).

3. Technical and biological alternatives

Various studies deal with brewery waste and we mentioned some of the ways investigated and their level of development Table 3. Firstly, biological treatment may be an interesting and environmental issue. Secondly, technical issues (use of regenerable filter-aids) may constitute a way to eliminate the problems induced by Kieselguhr. Finally, membrane filtration (MF) may provide an alternative to the conventional dead-end filtration with filter-aids such as diatomaceous earth (clarification) and a way to reduce waste volume (loss reduction) and indirectly water consumption (cold sterilisation).

3.1. Biological alternatives

The incorporation of brewery waste (spent grains) into fish-feed (carp) was investigated by Kaur and Saxena [14] in India. The better growth performance in fishes fed on diets containing brewery waste is attributed to the availability of good quality protein, as the waste contains more essential amino acids such as lysine, arginine and methionine than fish meal and about three times the level of these amino acids present in rice bran.

Industrial wastes, especially of organic origin, have a high potential for agricultural use. In Turkey, Kütük et al. [15] investigated the effects of beer factory sludge on soil properties and sugar beet growth. Increasing doses of brewery sludge has a significant effect on the vegetative growth of sugar beet plants. The best application level seems to be 10 ton/ha considering root development, this being the economic part of the sugar plant.

Marques et al. [16] found that waste brewery biomass of non-flocculent and flocculent types are promising biosorbents for the removal of Cu^{2+}, Cd^{2+} and Pb^{2+} in concentrations up to 1.0 mM from non-buffered aqueous solutions.

Anaerobic digestion constitutes an option to treat the brewery effluent. The fact that the anaerobic treatment system does not produce biological sludge is a key factor, as well as its ability to reduce chemical and biological oxygen demand (COD, BOD) and suspended solids at low hydraulic retention time. Etheridge and Leroff [63] report an industrial digester (volume 3300 m^3, flow rate 700 m^3/day) incorporating novel heating and mixing technologies with a demonstrated energy efficiency. Muroyama et al. [17] investigated at laboratory scale an original technology called up-flow anaerobic sludge blanket (UASB) process, which treats brewery organic wastewater with high efficiency in a sludge granular bed containing self-coagulated particles of anaerobic microorganisms as bio-catalysts.

3.2. Technical alternatives: regenerable filter-aids and membrane separation

Kieselguhr has been successfully used for decades in beer filtration but this material presents some disadvantages previously detailed. The scientific and industrial literature reports three trends for future beer clarification process: (1) the reduction of Kieselguhr consumption; (ii) the replacement of Kieselguhr by regenerable filter-aids; and (iii) the development of Kieselguhr-free processes (membrane filtration). To be convinced of the growing interest of the brewing industry in alternative

Table 3
Technical and biological alternatives to reduce brewery waste: level of development and scale investigated

	Type of development :	Academic		Industrial
	Scale of investigation :	Laboratory	Pilot-plant	Industry
Biological alter.	***Biological alternatives :***			
	• Spent grain as fish feed		←→	
	• Organic waste on agriculture ground		←→	
	• Waste brewery biomass as biosorbent	←→		
	• Anaerobic digestion	←→		←→
Technical alter.	***Regenerable filter-aids :***			
	• Polymeric granules	←→	←→	
	• Mixture of micro-beads coated with a polymer and polymer/cellulose fibres	←→	←→	
	Membrane processes :			
	• Tank bottom recovery	←→	←→	←→
	• Cold sterilisation	←→	←→	←→
	• Rough beer clarification	←→	←→	←→

issues, it is instructive to note the increasing number of publications and patents regarding with the improvement of conventional filtration and the protection of new filtration processes. We describe below the potential of alternative filter-aids and membrane processes.

3.2.1. Regenerable filter-aids

Kieselguhr consumption reduction may be achieved by optimising the existing process using different ways [18]: selection and characteristics of filter-aids, precoating and multistage filtration, automation of beer filtration system and filter-aid dosage rate, increasing filtration capacities, saving water for cleaning and regeneration by chemical and thermal treatment. However, the use of regenerated reusable Kieselguhr appears to be of limited industrial practice.

The opportunity to carry out the filtration with alternative and regenerable filter-aids seems very attractive. The filter-aid should satisfy food process requirements, be resistant to caustic solution and temperatures up to 100 °C (conventional regenerative conditions), exhibit specific mechanical properties (inert and rigid material), present a low specific surface but a high retention capacity (clarification) together with a high filtration efficiency. Regeneration of the used filter medium should not modify its initial performance. Recent results have been mentioned at a pilot-plant scale but none in industrial conditions. In the following are described the filter-aids used by Bonacheli et al. [19] and Rahier and Hermia [20].

The regenerable filter-aid developed by Interbrew and UCL (Université Catholique de Louvain, Belgium) is composed of polymeric granules [20] with specific properties (density, particle size, pore size, diameter, shape and specific surface). This material in combination with PVPP was used successfully for clarification and stabilisation of beer. Reported advantages of using this material are a single clarification–stabilisation step with high specific flow rate and long run times.

Meura Company [19] developed a filter-aid composed of a mixture of synthetic polymer or special cellulose fibers and 44–88 μm microbeads coated with a polymer which improves surface properties. This mixture combines the mechanical properties of the microbeads (incompressibility, low porosity) with the qualities of the fibres. Reported data specifies that filtration performance is equivalent to conventional Kieselguhr filters.

3.2.2. Membrane process

Considerations of the brewing process indicate two areas where membrane process (dead-end, cross-flow and dynamic filtration) might play useful roles [21]: (i) loss reduction in the brewing process, and (ii) as a technological alternative to the conventional solid–liquid separations. Loss reduction concerns two applications: the recovery of extract during the wort clarification and beer recovery from tank bottoms (fermentation and maturation vessels). At present, tank bottom recovery constitutes the principal membrane application in brewing. As a technological alternative, MF can be utilised in three applications: mash separation, clarification of rough beer, cold sterilisation of clarified beer before conditioning. Scientific studies and industrial applications concern essentially the clarification of rough beer and sterile filtration of clarified beer. A cost comparison between the membrane and conventional process is given in Table 4.

3.2.2.1. Loss reduction: recovery of fermentation and maturation tank bottoms. The membrane separated permeate can be recycled in the wort or in the maturation vessels [12,13] for fermentation tank bottom.

Table 4
Comparison of process cost for cold sterilisation (sterile filtration vs flash pasteurisation) and rough beer clarification (membrane filtration vs Kieselguhr dead-end filtration)

Operation	Membrane process	Conventional process
Cold sterilisation [45]	Dead-end filtration (cartridge filter), 0.26 €/hectolitre	Flash pasteurisation, 0.20 €/hectolitre
Clarification [62]	Cross-flow filtration, 0.44 €/hectolitre	Dead-end filtration with Kieselguhr, 0.43 €/hectolitre

The beer recovered from maturation tank bottom may be returned to the maturation vessel or sent for final clarification. However, the different compositions of the tank bottom beer may prevent a direct dilution into the rough beer before filtration [22–24]. Tank bottom concentrates may be sold as livestock feed.

Two fundamental differences exist among tank bottoms: (i) the fermentation vessels have high yeast cell content and high viscosity; (ii) the maturation vessels have high protein and polyphenol content, and fewer yeast cells and are characterised by low viscosity (close to that of beer). In order to recover "green beer" and "rough beer" from tank bottoms, natural sedimentation, centrifugation and a filter-press may be used. However centrifugation is expensive and may damage the permeate quality because of yeast cell degradation. Filter-presses provide a relatively low moisture solid discharge and consequently high extract recovery. However, sufficient clarification of the filtrate is not obtained. The use of MF is designed to produce: a permeate of acceptable quality including flavour and haze (defined by European Brewery Convention norm; [25], with minimal loss of original gravity, colour and bitterness while processing a retentate of between 2 and 4% dry weight to a minimum of 20%; to operate at low temperatures (close to 0 °C); to achieve economically sound flux and hygienic beer recovery. The presence of cloudiness or haze in beer is one of the more obvious quality defects discernible to the consumer. Several substances can cause haze in beer, but the most frequently encountered problem is due to a cross-linking of polyphenol (tannin) and protein.

Almost all of the membranes installed in breweries around the world are dedicated to the recovery of beer from fermentation and maturation tank bottoms. At present, these membrane applications have almost become industrial standards. The biggest challenge today is more a problem of commercialisation than a food-engineering problem. Since 1994 numerous industrial applications [26–32] have been reported in addition to scientific papers [33–38]. MF enables a 20–30% w/w concentration to be reached and several industrial units already use it. More than 50–60% of the yeast sediment is recovered as a high quality beer (equivalent to a volume reduction ratio of between 2 and 3). Membrane filtration becomes competitive in comparison to the filter-press for waste reduction. The recovered permeate recycled in the brewing process at a rate of 2–5%, allows beer loss and costs to be reduced. Various systems are in use and it has been shown that ceramic (0.4–0.8 μm; [26] or polysulfone (0.6 μm; [34] membranes concentrate solids from 12–15% to 20–22%. The payback is less than 2 years regarding the recovery of sterile beer from yeast beer with 0.4–0.8 μm pore diameter multi-channel ceramic membranes installed in 1 million hectolitre capacity breweries. Bock and Oechsle [28] explained that brewing plants are running with ceramic membrane made of α-aluminium oxide (multi-channel membrane, 19 channels; length, 1020 mm; mean pore diameter, 0.80 μm). Surplus yeast can be processed with about 17–20 l/h per m^2, up to a concentration of 20% w/w (transmembrane pressure up to 3 bar) and three process options exist: batch, semi-batch and continuous. This material can be cleaned in place since it is resistant to caustic, acid and oxidising sterilants even at high temperature (above 90 °C). Snyder and Haughney [37] describe a new system called vibrating membrane filtration (VMF) produced by PallSep. The system differs from traditional cross-flow filtration systems in that the shear at the membrane surface is generated mechanically (by 60 Hz vibrational energy) and not from high cross flow rates. Recovery of beer from surplus yeast can be achieved with a filter disc of PTFE membrane with the same performances as the other processes.

3.2.2.2. Technical alternatives: and cold sterilisation and rough beer clarification

3.2.2.2.1. Cold sterilisation of clarified beer. The clarification of rough beer is usually followed by pasteurisation so as to ensure the microbiological stability and the conservation of beer. Currently, heat treatment is mainly performed by flash pasteurisation (plate heat exchanger or tunnel pasteuriser) before conditioning. Conventional heat treatment requires water loops to heat and cool the product and also induces an additional water and energetic consumption.

Sterile filtration appears interesting and allows the elimination of the organoleptic problems induced by heat processing [39,40]. MF will have to face several challenges: to produce a microbe free beer without a negative change in beer quality, whilst operating at low temperatures (close to 0 °C); to ensure beer stability (biological, colloidal, colour, aroma and flavour, foam stability); to achieve economical flux. Provided it fulfils these considerations, MF can be a truly operational alternative to pasteurisation and dead-end filtration with cartridges. Cold-sterile filtered beer (draught beer or bottled beer) corresponds to a strong demand from consumers for quality and natural products. The objective of eliminating heat treatment of the finished product is achieved with membrane cartridge systems (dead-end filtration) installed directly upstream of the filling system [41,42]. However, cold sterilisation by cross-flow membrane is under trial and is feasible in an industrial context [43–45]. Krottenthaler et al. [45] report that the technical developments of membrane filtration (membrane lifetime, running time, cleaning procedure, cost reduction) as well as market trends reveal constant improvement. Membrane filtration offers a way of safe and careful product stabilisation for the brewing industry. Financial aspects become more and more attractive, for instance the cost of flash pasteurisation is assumed to be 0.20 €/hl whereas membrane filtration is around 0.26 €/hl of clarified beer.

3.2.2.2.2. Clarification of rough beer. Beer clarification is probably one of the most important operations, when rough beer is filtered in order to eliminate yeast and colloidal particles responsible for haze. In addition, this operation should also ensure the biological stability of the beer. It should comply with the haze specification of a lager beer in order to produce a clear bright beer. Standard filtration consists of the retention of solid particles (yeast cells, macro-colloids, suspended matter) during dead-end filtration with filter-aids. The variety of compounds (chemical diversity, large size range) to be retained makes this operation one of the most difficult to control. However, membrane processes should satisfy the same economic and qualitative criteria [24,46] than conventional dead-end filtration. MF should be able: to produce a clear and bright beer with similar quality to a Kieselguhr filtered beer; to perform a separation in a single-step without additives; to operate at low temperature (0 °C); to achieve economic flux.

Among the potential applications of cross-flow microfiltration, the clarification of rough beer represents a large potential market (approximately 200 000 m^2 surface). Industrial experiments however, encountered two main problems: (i) the control of fouling mechanisms and (ii) the enhancement of permeate quality Fig. 2. Since 1995, a lot of works have indicated the economic and scientific stakes of the clarification of rough beer. Recent scientific and industrial studies [47–61] have dealt with (i) fouling mechanisms; (ii) the relationship between quantitative and qualitative performances; (iii) the development of alternative membrane filtration such as membrane structure and dynamic filtration; and (iv) industrial applications.

MF suffers from a low permeate flux in comparison to the conventional dead-end filtration with filter-aids such as diatomaceous earth (usual flux ranges from 100 to 500 l/h per m^2). However, the first industrial plants are running: for example, a MF unit of rough beer with a capacity of 10 000 l/h [58,60,61] at Heineken. The plant contains 10 hollow fibre modules X-Flow R100 (pore size, 0.45 μm; length, 1 m; inner diameter, 1.5 mm; filter area, 9.3 m^2). The key of this process is based on a specific cleaning procedure. It combines a caustic step, an acidic step and a strong oxidative step (2 h in duration), which is successful in achieving a run time between 7 and 20 h for about 120 runs. Heineken and Norit Membrane Technology have patented this

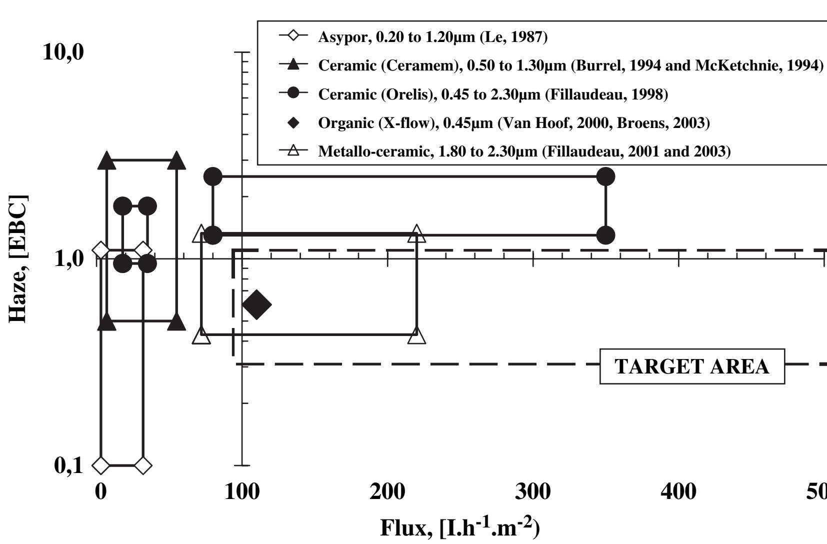

Fig. 2. Flux versus haze in the clarification of rough beer by MF (target area: haze < 1 EBC and flux > 100 l/h per m^2). ◇, Asypor, 0.20–1.20 μm [23]; ▲, ceramic (Ceramem), 0.50–1.30 μm [33,64]; •, ceramic (Orelis), 0.45–2.30 μm [47]; ◆, organic (X-flow), 0.45 μm [59,61]; △, metallo-ceramic, 1.80–2.30 μm [53,54].

procedure. Filtration is accomplished at 0 °C, 2 m/s flow velocity and up to 1.6 bar transmembrane pressure. During filtration, 10 min periods of back-flushing are applied every 2 h to remove the reversible fouling that has built up. The flux is maintained at 100 l/h per m^2 and clarified beer fulfils the European Brewery Convention (EBC) standard in terms of turbidity (close to 0.6 EBC unit), bitterness, total extract, colour, and protein content. The cost of membrane filtration for bright beer is about 0.40 €/hl. Up to 2007, the total cost for membrane filtration is expected to be 20–30% cheaper than that for Kieselguhr filtration [62].

4. Conclusions

Water and wastewater management in breweries remains a critical and practical problem. Brewing industries exhibit a wide range of production capacities, which induces a strong difference in waste and water management. All breweries try to keep disposal costs low whilst the legislation concerning waste disposal is becoming more and more stringent. Water consumption is not only an economic parameter but also a tool to determine process performance. Spent grains, Kieselguhr sludge, yeast surplus and waste labels represent the most important wastes. The most common treatment and their estimated cost are described. However, biological and technical alternative treatments are appearing that are designed to reduce water consumption and wastewater volume.

Biological alternatives are efficient treatments if the effluents satisfy strong and specific properties and use conditions. Technical approaches such as membrane filtration are not subject to such severe conditions and MF in brewing offers several advantages, some of which are already being employed. MF could be interesting for recovering extract from loose trub suspension and for separating wort from mash. It constitutes an emerging application for the clarification of rough beer and cold sterilisation of clarified beer. MF is already an industrial standard for the treatment of fermentation and maturation tank bottoms.

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