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DIFFERENT TYPES OF INDUSTRIAL FERMENTORS AND THEIR ASSOCIATED OPERATIONS FOR THE MASS PRODUCTION OF METABOLITES

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ABSTRACT

The process of fermentation involves production of gases, alcohols or organic acids, by the consumption of sugars using pure culture of microbes. Fermentation Process is carried out in specially designed vessel called as fermenter or bioreactor. This vessel is utilized to support the growth conditions of microorganisms carrying out fermentation. Its design and construction must provide the optimum environment conditions to the microorganisms. Fermenters are usually the cylinder shaped vessels having spherical top or bottom with varying sizes ranging from liters to cubic meters made up of stainless steel or glass. In fermenters are biological reactions are allowed to occur under very controlled conditions. The designing and operation of a fermenter is mainly based upon the organism used for fermentation, optimum conditions required for the desired product formation, value of the product and the production scale. It also involves investment and the running cost. There are various types of bioreactors used in fermentation industry and their operations are mainly based upon the microbial cells carrying out fermentation and the product which has to be achieved after that fermentation. This article comprises a brief description of various types of fermenters, their operations, applications, advantages and disadvantages. However further efforts are needed to boost up technology and performance of bioreactors. Strategies must be designed to lower cost of fermentation and construction of fermenters no matter which product is being produced. Novel and innovative industrial products can be developed very easily by establishing a more sustainable industrial production.

KEYWORDS: fermenters, bioreactors, fermentation, fluidized bed fermenter, baffle.

INTRODUCTION

Fermentation is a process in which sugar is consumed in the in availability of oxygen, as a result of metabolism, gases, alcohol or organic acids are achieved as a byproduct (Fernandez, 1996). Fermentation Technology is the study of the process of fermentation, the techniques employed in it and its applications (Durand, *et al*., 2003) Fermentation is not only based upon the reactions occurring in the fermenter but it is also based upon the activities that form the base of the reactions occurring in the fermenter. However, fermenter is considered as a heart of fermentation process (Diaz, *et al*., 2008) Fermentation technology focuses upon the study, control and optimization of fermentation reactions and is based upon many other fields such as biochemistry, microbiology, genetics etc (Panda and Ali, 2008).

Fermentation at an industrial level is carried out in specially designed vessel called as fermenter or bioreactor. This vessel is utilized to support the growth conditions of microorganisms carrying out fermentation (Durand and Chereau, 1987). Its design and construction must provide the optimum environment conditions to the microorganisms. Fermenters are usually the cylinder shaped vessels having spherical top or bottom with varying sizes ranging from liters to cubic meters. The material used in the construction of fermenter is stainless steel or glass. In fermenters are biological reactions are allowed to occur under very controlled conditions (Bhagry, *et al*., 2008). The designing and operation of a fermenter is mainly based upon the organism used for fermentation, optimum conditions required for the desired product formation, value of the product and the production scale. It also involves investment and the running cost. No aseptic condition is required for the production of large volume and low valued product such as alcohol and it is mainly done in simple fermenters whereas high valued products having low volume require carefully designed fermenters and aseptic conditions (Diaz, *et al*., 2008).

Designing of the fermenter

A fermenter must be designed on the basis of biological processes to be carried out in them. Following aspects must be taken under consideration. The substrate and product concentration in the reaction vessel is low. Both the substrate and product can stop the metabolic process.

Microbial growth, metabolism and formation of desired product depends upon the nutritional requirement of cells e.g. salts and oxygen. It also depends upon the maintenance of optimal growth conditions such as temperature, pH(Engassar, 1988).

Mechanism of metabolic reaction is also influenced by the presence of certain substances in the reaction mixture such as effectors, precursors and inhibitors (Diaz, *et al*., 2008). If there is any contamination present in the reaction vessel it will also be metabolized by the microbes. The contamination may involve raw materials such as cellulose, molasses, mineral oil, starch, waste water etc (Durand, et al.,2003). Microorganisms are very sensitive to sensitive sheer, thermal and chemical stress. The reactions occur in solid-liquid-gas phase systems (Engassar, 1988).On the basis of above mentioned requirements, we can say there is no universal biological fermenter. The basic representation of fermenter is shown in figure 1.

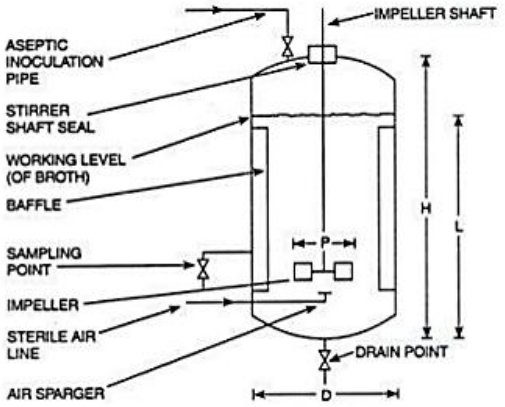

Figure 1: Basic design of fermenter.

General features of an ideal fermenter

The major characteristics of an ideal fermenter are described as follows. Material used in the construction of a fermenter must be able to bear high pressure and temperature conditions mediated by the fermentation medium. Furthermore, the material used for the construction of a fermenter must be selected according to the nature of fermentation which has to be carried out in it (Durand, 2003).

The fermenter material must be resistant to corrosion, It must not have any toxigenecity on the microbial culture and it must not affect the purity of product. A fermenter should provide easy handling and control of microbes causing contamination. There must be an inlet present in the fermenter to provide easy and aseptic inoculation (Abbot, 2003). If aerobic fermentation has to be carried out, proper exposure to oxygen is necessary hence an aerating device must be present in the fermenter (Durand, et al.,2003). There must be a stirring device in fermenter for equal distribution of air, microbes and nutrients. In order to avoid vortex formation, baffles must be present in fermenter (Diaz, *et al*., 2008). There must be a way to control temperature and pH of the fermenting medium.

There must be a sampling valve resent in fermenter to withdraw media and product time by time for laboratory analysis (Garcia and Gomez, 2009). A draining outlet should be present for complete removal of medium from the fermenter and for the recovery of product. A large hole should be present at the top of fermenter in order to get access to the inside of fermenter for various purposes such as repairing, cleaning etc (Durand, 2003).

Types of Bioreactors/Fermenters

There are various types of bioreactors used in fermentation industry and their operations are mainly based upon the microbial cells carrying out fermentation and the product which has to be achieved after that fermentation. Following are the major types of fermenters used in the industry and the other fermenters are the subtypes of these main fermenters (Panda and Ali, 2008). Mechanically Agitated Fermenter, Non-mechanically agitated fermenter, Non-agitated fermenter. The other types are described as follows. Continuous stirred tank fermenter, Tower fermenter, Deep jet fermenter, Batch fermenter, Cyclone column fermenter, Gas lift fermenters, Air lift bioreactor, Fluidized bed bioreactor, Bubble column bioreactors, Wave bioreactors, Sparged tank fermenters, Photo bioreactor, Membrane bioreactor, Novel see saw fermenter, Rotary drum bioreactor, Mist bioreactor.

Continuous Stirred Tank Bioreactor

Stirred tank fermenter remains the choice in more than 70% fermentations although it is not the best type of fermenter. Main functions operated in stirred tank fermenter are described as follows.

The continuous stirred-tank reactor (CSTR), also known as vat- or backmix reactor, is a common ideal reactor type in chemical engineering. A CSTR often refers to a model used to estimate the key unit operation variables when using a continuous agitated-tank reactor to reach a specified output. The mathematical model works for all fluids: liquids, gases, and slurries.

The behavior of a CSTR is often approximated or modeled by that of a Continuous Ideally Stirred-Tank Reactor (CISTR). All calculations performed with CISTRs assume perfect mixing. In a perfectly mixed reactor, the output composition is identical to composition of the material inside the reactor, which is a function of residence time and rate of reaction. If the residence time is 5-10 times the mixing time, this approximation is valid for engineering purposes. The CISTR model is often used to simplify engineering calculations and can be used to describe research reactors. In practice it can only be approached, in particular in industrial size reactors (Fontanna, *et al*., 2009).

Baffles and rotation stirrer is also present which is positioned either at the top or bottom f fermenter. Condition in the fermenter are made steady by employing principles of chemostat or turbidostat. Chemostat is involved in adjusting flow rates of the fermenter to the required value and is maintained also which further make fermenting microbes, substrates and product to reach their natural levels (Fontanna, *et al*., 2009).Furthermore, turbidostat is involved in checking and maintaining the turbidity of the fermenting material. Turbidity is an indirect measure of number of growing microbes inside the fermenter (Laska & Cooney, 1999). The use of bacteria and yeasts provide the most successful continuous fermentations providing us desired products in form of primary and secondary metabolites. The basic representation of fermenter is shown in figure 2.

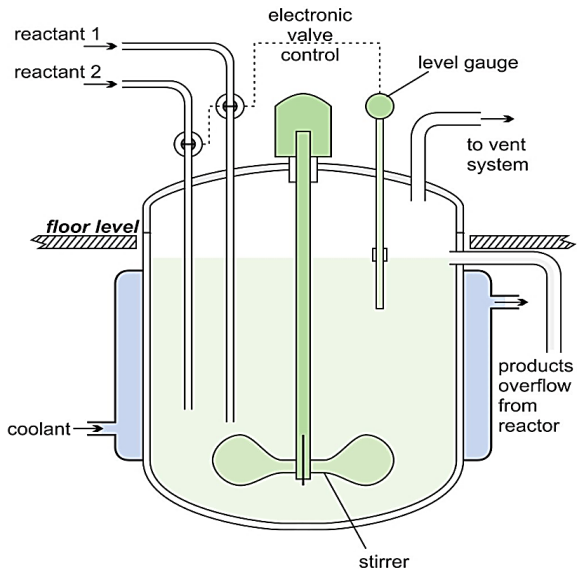

Figure 2: Continuous stirred tank bioreactor.

Advantages of Stirred Tank Bioreactor

Continuous stirring. Temperature control and maintenance. Simple design and construction. Less labor cost. Cleaning is quite easy. A number of microbes can be used for fermentation. Zone of culturing and zone of mixing is separated in order to avoid abrasion by immobilized cells (Lee, *et al.*, 2009).

Tower fermenters

Tower fermenters are mainly used t carry out continuous fermentation. This system was ist time used by Bass in 1870s which was 8.5m high and 1 m in diameter. This fermenter was developed to overcome the drawbacks faced by batch fermentation. It is mainly used in brewing industries for production of beer (Fernandez, 1996). A typical tower fermenter consists of a yeast gradient and a gradient of wort also going up the tower. The purpose of this multi stage fermenter is to provide flow of process with the help of gravity. Bulk of raw materials, water and malt are elevated to the top of fermenter first which then come downward without the need of any pump (Zhang, et al., 2009). An inlet is present at the bottom where as an outlet is present at the top. It also carries insulating jackets which are meant to maintain optimum temperature conditions for organisms to grow. Baffles are also present which are meant for agitation (Pandy, *et al.*, 2001). Figure 3 shows the basic design of tower fermenter.

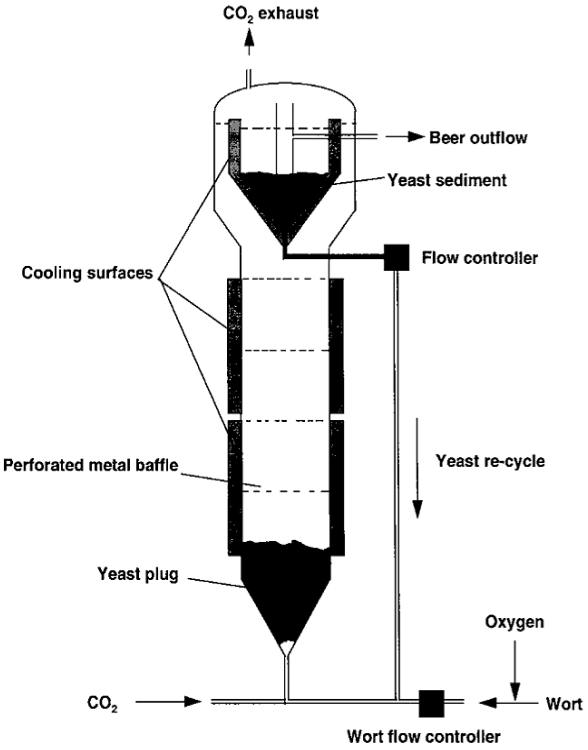

Figure 3: Tower fermenter.

Bubble Column Bioreactors

Bubble column fermenters are mainly developed for sensitive cells. They consist of a cylinder type vessel having a device at the bottom which is involved in the distribution of gases. The gas is sprayed via this distributor in the liquid phase or liquid solid phase in the form of bubbles. They are widely used in chemical, petrochemical, biochemical and metallurgical industries (Degaleesan, 2001; Kantarcia et al, 2005). In order to provide easy liberation of bubbles and foam break, the top of cylinder is kept relatively large. Aeration is done by using compressed air using spargers fixed at the bottom of the vessel. No other internal components are present in the cylinder. Gas sparger is important as it has ability to alter characteristics of bubbles such as size, shape etc. there plates present having small orifices which control the formation of small sized pores (Astron and Hagglun,1984). Common gas spargers include perforated and porous plates, membranes, eing type and arm spargers. An important key parameter in bubble column bioreactor is Gas holdup. It is described as the volume of the gas phase surrounded by the gas bubbles (Luo et al, 1999). Design and analysis of bubble columns s based upon gas holdup, so it is very important (Kantarci et al, 2005). The basic representation of this fermenter is shown in figure 4.

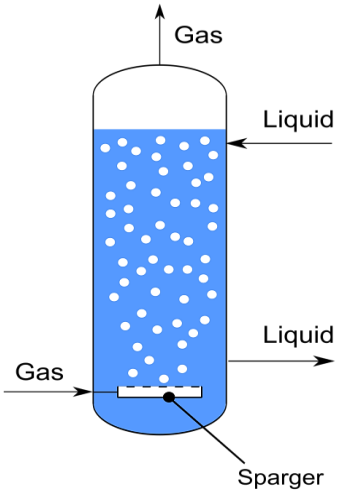

Figure 4: Bubble column bioreactor.

Bubble columns are involed in the production of proteins, other enzymes and antibiotics (Kantarci et al, 2005). Important parameters involved in bubble column fermenters involve: Ascending speed of bubble, its residence time, interfacial space, mass transfer and hold up value (Luo et al, 1999). Advantages of Bubble Column Fermenter are as follows; gas introduced from the downward plays role for both mixing and aeration, used in treatment of waste water, used in production of citric acid, baker's yeast and beer (Kantarci et al, 2005).

Gas lift Fermenters

No mechanical stirrer is present. Heat transfer and mixing is done by pumping gas through the liquid medium. Gas compressors provide compressed gas a s a power transmission system. If gas is in less compressed form, the efficacy of fermenter is disturbed. Air lift fermenters are a type of gas lift fermenters (Flickinger & Drew, 1999). Figure 5 shows the diagram of gas lift fermenter.

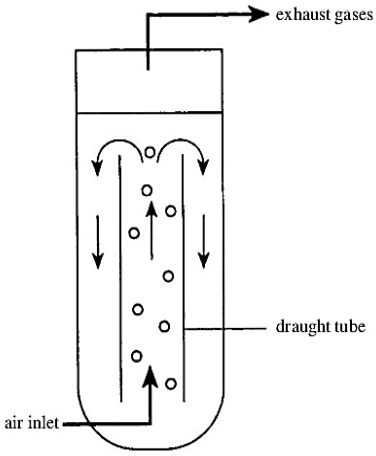

Figure 5: Gas lift fermentor.

Air lift Fermenters

Air lift fermenters have a little variation with that of bubble column fermenters. One main difference is the presence of a central tube and other channels having role in the proper mixing and circulation of the fermenting culture and medium(Fontanna, *et al*., 2009). This results in the reduction of bubbles amalgamation circulating within the reactor and equalizing the stress induced by the mixing. It is named as airlift fermenter on the basis of contact between gas-liquid or gas-liquid-solid which is made by the circulation of fermenting fluids in cyclic form (Flickinger & Drew, 1999).

In these type of bioreactors, two interconnected zones are present made by the use of baffles in which medium is added. One zone is named as riser in which the air is pumped whereas in the other zone no ar is added and it is the down comer. Dispersion of air particles move up the riser zone whereas downward flow occurs in the down comer (Chakrabarty, A., 2001). These bioreactors are mainly used for aerobic fermentations. Adequate pumping is involved in controlled flow and recycling of liquid. Because of their well-defined efficiency, they are preferable in waste treatment, production of methanol and SSP's production (Abbot, 2003). Air lift fermenter is displayed in figure 6.

Following are the important types of airlift bioreactors.

Internal-loop airlift bioreactors

It consists of a single container having a draft tube in the center which is involved in creating interior liquid circulating channels. They have a very simple design and its volume and circulation is maintained at a fixed rate to carry out fermentation (Garcia and Gomez, 2009).

External-loop airlift bioreactors

These bioreactors have an external loop in order to promote circulation via separate independent channels. Several modifications can be done in these fermenters in order to fulfill various type of fermentation requirements. However, it is more suitable to say that airlift bioreactors bio reactors have better efficiency than bubble columns specifically for denser microbial suspensions as mixing of contents is far better than that of bubble columns (Chakrabarty, A., 2001).

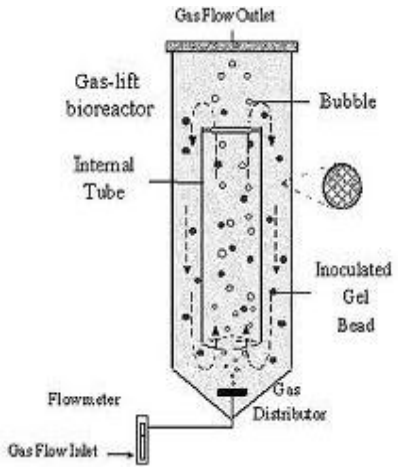

Figure 6: Air lift fermentor.

Two-stage airlift bioreactors

These bioreactors are involved in temperature dependent product formation. It has two bioreactors. In ist bioreactor, growing cells are present which has a maintained temperature of 30ºC. these cells are then pumped towards another bioreactor which has temperature of 42ºC.a problem in this type of bioreactor is the immediate change of temperature from 30-42ºC (Garcia and Gomez, 2009). Both bioreactors carry valves further connected by transferring tube and a pump. Cell culture grown in its bioreactor and further process is carried out in the second reactor (Flickinger & Drew, 1999). Various types of fermenters are shown in figure 7.

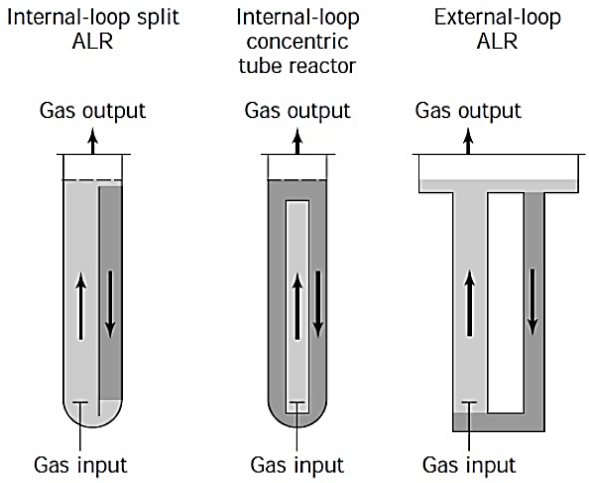

Figure 7: Types of air lift fermenters.

Advantages of airlift bioreactor

Because low sheer force is generated, animal and plant cells can be operated. Sterility can be maintained easily because there is no agitation. Due to height of the vessel, pressure increases at the bottom hence increasing mass transfer. A vessel of very large size can be used (Flickinger & Drew, 1999).

Batch bioreactors

This type of bioreactor is widely used in processing industries. It is involved in variety of fermentation processes i.e. crystallization process, various chemical reactions, dissolution of solids, mixing of product, batch distillation, extraction of liquids and polymerization processes (Astron and Hagglun,1984).It consists of a tank having and agitator and an incorporated heating and cooling system. They are of variable sizes ranging from less than a liter to higher than that of 15000 liters (Flickinger & Drew, 1999). Their fabrication is done using steel, glass lined steel, glass alloys etc. the internal solid and liquids are charged by using electric connections. Gases produced as a result of fermentation are discharged from the top whereas liquid product discharges from the bottom (Chakrabarty, A., 2001). Batch reactor is shown in figure 8. Advantages of the batch reactor are; it is advantageous because of its versatility, a serious of various operations can be carried out in a single vessel, it is useful in treating potent and toxicogenic compounds (Ashley, Mitchel and Hovis, 1999).

Packed bed bioreactors

These are also called as fixed bed bioreactors. There use is common in engineering of waste water management in case of biofilms. This is very important technique and was recognized after usage of other techniques like cell immobilization. Biocatalyst used in cell immobilization is carefully packed initially and the columns are given nutrients (Leite, 2008). They are used when the reaction rate is affected by substrate inhibition. These bioreactors can alter their flow during the process because of change in porosity. During fermentation compaction may takes place with soft gels due to which may cause drop of high pressure and these gels can be damaged; these soft gels include alginates and carragenam (Ashley, Mitchel and Hovis, 1999). To avoid this situation tapered beds are used generally along with other beds like inclined, rotary with horizontal, only horizontal etc. These beds are in category of plug flow reactors where no back mixing will occur but the turbulence may cause channeling and as well as the back mixing, which results in changes of fermentation characters. Paked bed reactor is shown in figure 9.

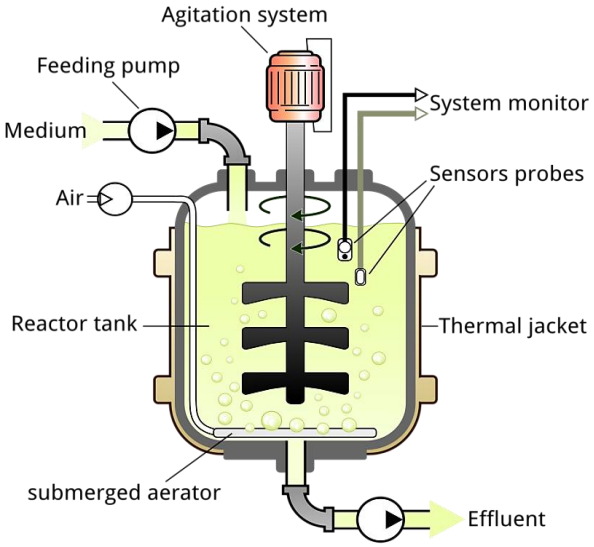

Figure 8: Batch bioreactor.

Advantage of Packed Bed Bioreactor

Catalyst involved in these rectors causes higher conversion per unit mass of the products than that of other catalysts. Low cost is required for their operation (Ashley, Mitchel and Hovis, 1999). Continuity of operation is present. Separation of catalyst is very easy. Process can take place effectively even at higher pressure and temperature (Leite, 2008).

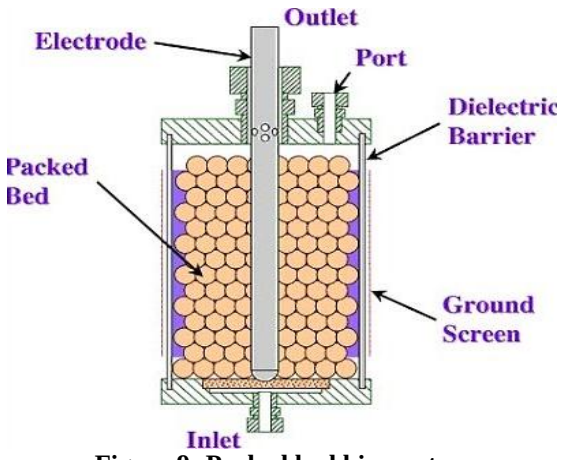

Figure 9: Packed bed bioreactor.

Fluidized bed bioreactor

The name represents the use of fluid in this where the particles are distributed in a fluid which is in flow. When gas particles are mixed in it with fluid, the particles are not equally distributed at that point (Fujjan, *et al*., 2002).One of the important feature is these bioreactors is that the porosity takes place from bottom to upwards and there is reduction in motion of particles. This void age represents the presence of space available as well as it shows the presence of microbes which are expressed in wet volume with the bed volume (Abbot, 2003). In this fermenter there are changes in microbial presence which enhances the presence of small sized particles more on top than the bottom and for the larger sized particles; they are more abundant in bottom (Ashley, Mitchel and Hovis, 1999). These small particles have less velocity and the arrangement of particles is done in a way that these small sized particles have porosity high. The fermenter used for the beer production is called tower fermenters and are working on these principles. Yeast cells are used in beer formation, first the suspension is made in the media and the motion is upwards, any trapped residues are sedimented and returned at tower top (Astrom and Hägglund, 1984). Figure 10 shows the diagram of this bioreactor.

Construction of fluidized bed bioreactor

There is elongated vertical cylinder in the fermenter with the diameter to length ratio (1:10). There is a separator present at the top of fermenter which is used in the separation of gas particles and liquid, which is a result of reaction (Leite, 2008). Inside of separator there is a lone called quiescent. This is free from gas and beer is cleaned here and separated, after separation the cells are moved down to main area of tower (Fujjan, *et al*., 2002). These large sized yeast cells are important in formation of alcohol and fermentation process. The rate of flow should be in control otherwise the cells can be washed out if the flow rate is increased. This would create yeast in insufficient concentration (Robinson, 2003). Good concentration of yeast cell is represented by weight 25%, which can reach on tower up to 30% or 35% on the bottom , whereas on the top it may each up to 10% only (Abbot, 2003).

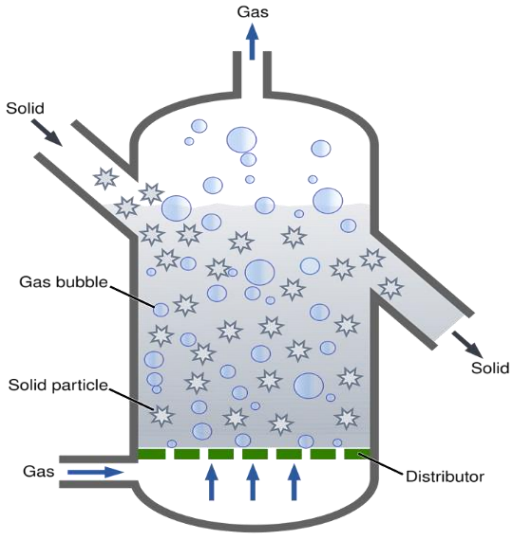

Figure 10: Fluidized bed bioreactor.

As the movement of the machine causes to change the gravity of components used, there is continuous fall in the gravity related to the nutrients, which progressively enhances from bottom to top. Initially it will fall down the bottom of tower, then it will reach to the mid and then fall to top. This is the result of sugars production during the fermentation reaction (Abbot, 2003).

Advantages of Fluidized Bed Reactor

Uniform Particle Mixing

There is proper and uniform mixing in fluidized beds due to fluid nature of the solid particles. Due to proper mixing the formation of product is uniform which is not easy to achieve in other fermenters. There are no gradients in concentration (radial or axial) which promotes smooth product formation and also enhances the quality and rate of efficiency (Robinson, 2003).

Uniform Temperature Gradients

There is proper maintenance of temperature and heat because there is increase and decrease of heat due to chemical reaction that are taking place in the fermenter. There are some areas on the bed labeled as hot spots and cold spots (Fujjan, *et al*., 2002). These spots are avoided during the process because they may hinder the process. These spots indicate the temperature fluctuation and these can cause product degradation. These are very suitable for the exothermic reactions because the heat transfer rate is high (Leite, 2008).

Ability to Operate Reactor in Continuously

These beds have ability to introduce the reactants timely and withdraw the products as the reaction is continuously in process. This makes space for the next reaction to occur and also the previous products don't hinder the current reaction. These conditions help to improve the product quality and their efficiency (Ju, Chase and Akron, 1992).

Membrane Bioreactor

These bioreactors can be applied to microbes involving processes like fermentation (alcoholic), acid (vinegar) production, waste water treatment etc. In this solute and solvents are added in proper amounts along with the enzymes (Gan, et al., 2002). For this purpose the enzymes are introduce using filters and pumps. These filter membranes are used for introduction of substrates and release of product (Lee, *et al.*, 2009). The membrane acts as a filter and don't let the enzymes to leave the bioreactor, stirrer is used for the mixing. The materials used in the membrane are cellulose acetate, polysulfonate and polyamide (Bartolo, *et al*., 2000). Advantages of membrane bioreactor are as follows; there is very less enzyme loss due membrane presence. There is continuous addition of enzyme due to which enzyme lost during reaction is covered (Bartolo, *et al*.,2000). The enzyme can be replaced easily by the substrate (Gan, et al., 2002).

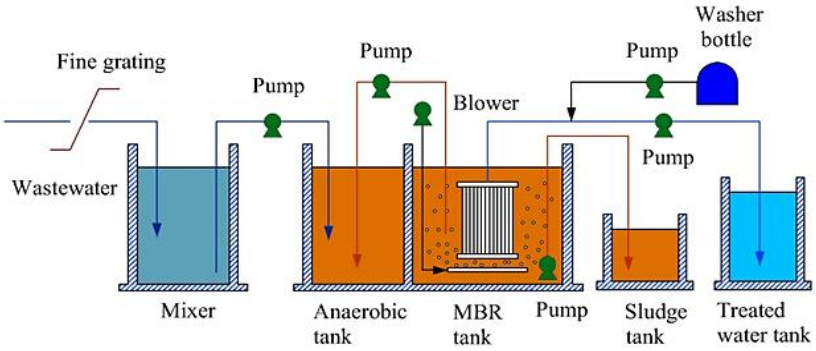

Figure 11: Membrane bioreactor.

Photo bioreactor

These bioreactors are involved in fermentation processes which are to be carried out in the presence of light either sunlight or artificial light (Astron and Hagglun, 1984). This is a bioreactor that is used in the propagation of microorganisms utilizing light; these microbes are phototrophic in nature. These microbes have ability of photosynthesis like green plants and they can generate biomass using light (Hoekema, 2002). Because of the high expense by the use of artificial light, natural illumination i.e. sun is preferred. Important products produced by the use of photo bioreactors are asthaxantin ad p-carotene. Commonly glass or transparent plastic is used in their construction. They consist of an array of glass or tubes which are meant to capture light. Microbial culture is being circulated through these tubes and arrays by the use of airlift or centrifugation pumps (Lee, *et al.*, 2009). Cell sedimentation has to be avoided in this case which is done by the use of continuous cultures. Proper light penetration must be maintained and heating of tubes must be avoided by the use of cooling systems. The operation of photo bioreactors is continuous in nature and temperature is maintained at 35-40˚C. Fungi and cyanobacteria are used as microbial cultures, growing in sunlight and producing desired fermented products at night (Gan, *et al*., 2002).

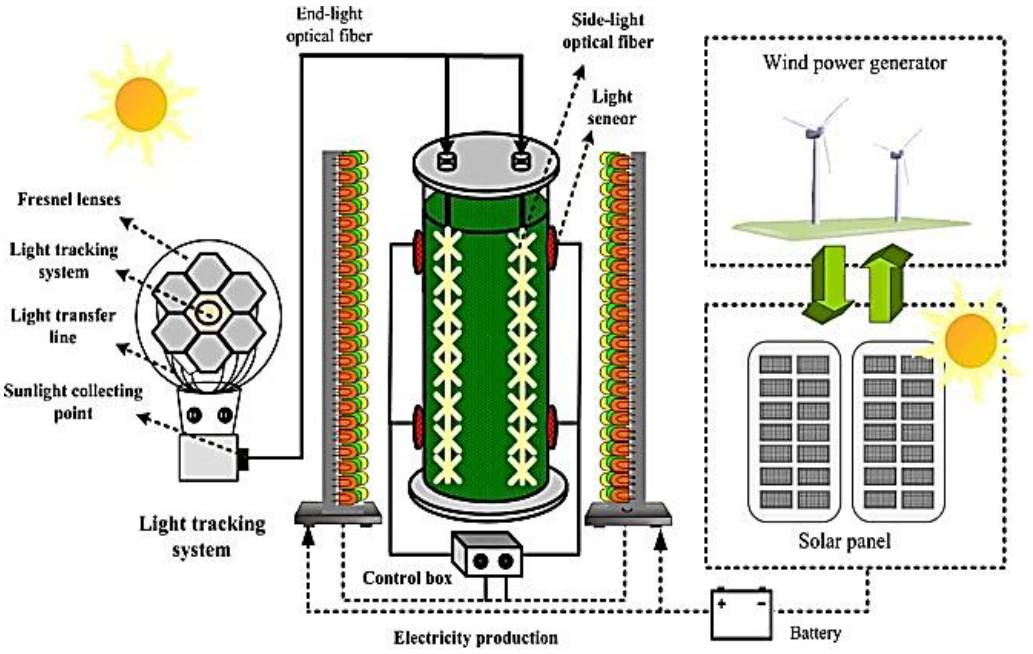

Figure 12: Photo bioreactor.

Advantages of Photo bioreactor

Higher productivity rate can be achieved by using these bioreactors.They provide large surface to volume ratio to carry out fermentation process. Gas transfer can be controlled in a better way. Evaporation of growth media is reduced. The batch is protected from contamination (Gan, *et al*., 2002). There is reduction of fouling due self-cleaning process of the tube. Algae are cultivated in a controlled way so its production is high. It is 10 to 20 times greater in this reactor than the bag reactors. Light usage is maximum in photo bioreactors which results in increased yield and productivity. Uniform temperature is provided (Hoekemma, 2002).

Wave Bioreactors

Wave bioreactors are widely used to cultivate tobacco, grapes and apple suspension. In this type, the platform is continuously in wave like motion hence provide continuous mixing and transfer of oxygen throughout the vessel providing very adequate environment for microbes to grown(Robinson, 2003). This bioreactor is made up of stainless steel with linear motor control system involved in rocking. An integrated heater pad is present to control temperature. Aeration is properly controlled. Dual cell bag control systems are also present (Eibl and Eibl, 2006). Advantages of Wave bioreactors are; no sterilization is required. Easy in operation. Provide protection against cross contamination. Time saving occurs, low cost. Reduced foaming occurs (Robinson, 2003).

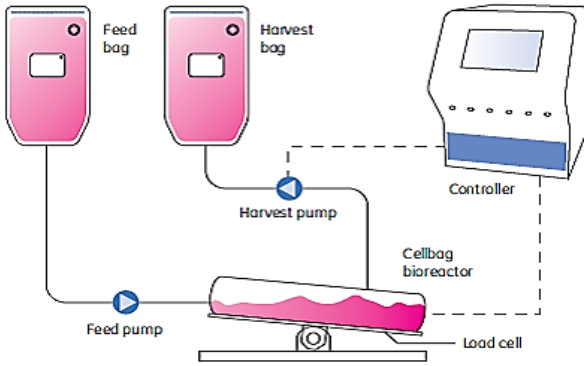

Figure 13: Wave bioreactor.

Deep Jet Fermenter

It is mainly designed on the principle of continuous culture fermenter. Mechanical power is given as input using a pump which is involved in circulating the medium. Two gas entrainer nozzles are present i.e. ejector and injector (Astrom and Hägglund, 1984). A high power jet is used for entraining the gas into the liquid present in the fermenter. The exhaust gas is removed from the hole present at the top and from the circulation pump which is involved in passing the degassed liquid which then pass to the supplementary cooler. High gas dissolution rate is achieved however; high power is required to operate this system (Ju, Chase and Akron, 1992).

Sparged tank fermenters

This type of fermenter also belongs to non-mechanically agitated fermenters. Gas is introduced from the bottom with the help of a nozzle or porous plated. While moving through the liquid, gas bubbles rise and get dispersed again due to the presence of baffle plates arranged horizontally (Lee, *et al.*, 2009). Advantages of Sparged tank fermenters: As agitation shaft is not present, the risk of contamination at the entry point of vessel reduces. The consumption of power is reduced by the absence of agitator which requires high power and also a single agitator is not sufficient to carry out agitation. Cooling of fermentation medium is achieved by the evaporation of gas particles from the liquid medium (Ju, Chase and Akron, 1992).

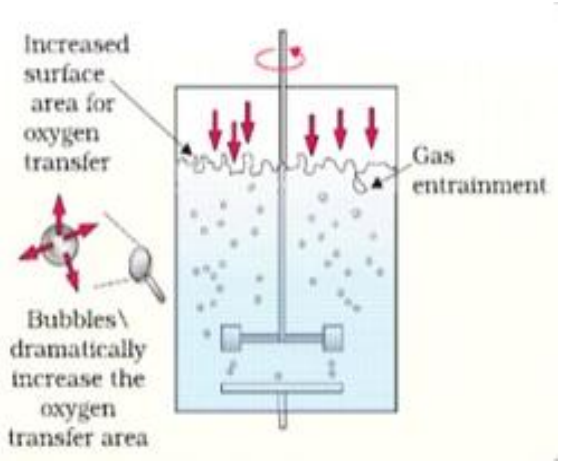

Figure 14: Sparged tank fermenters.

Rotary drum bioreactor

Rotary vacuum filter drum consists of a drum rotating in a tub of liquid to be filtered. The technique is well suited to slurries, and liquids with a high solid content, which could clog other forms of filter. The drum is pre-coated with a filter aid, typically of diatomaceous earth (DE) or Perlite. After pre-coat has been applied, the liquid to be filtered is sent to the tub below the drum. The drum rotates through the liquid and the vacuum sucks liquid and solids onto the drum pre-coat surface, the liquid portion is "sucked" by the vacuum through the filter media to the internal portion of the drum, and the filtrate pumped away.

The solids adhere to the outside of the drum, which then passes a knife, cutting off the solids and a small portion of the filter media to reveal a fresh media surface that will enter the liquid as the drum rotates. The knife advances automatically as the surface is removed. (Wang et al, 2010). They recently got attention for the production of biofuels. Advantages of rotary drum bioreactor: Gentle and uniform mixing is provided by improved baffles design. No sheer force is generated because of absence of agitator. High oxygen transfer (Chakrabarty, A. 2001).

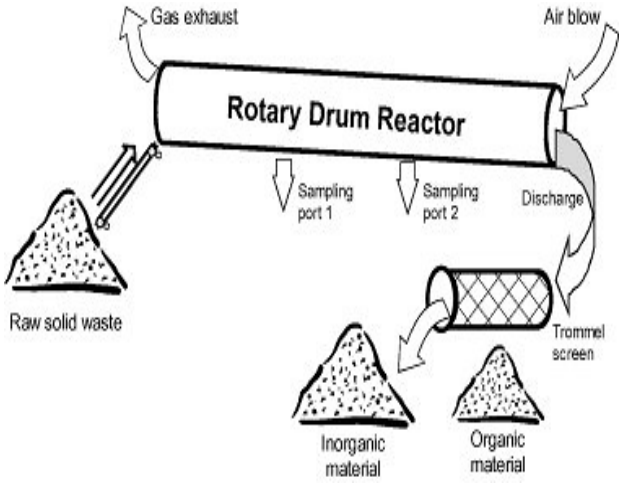

Figure 15: Rotary drum reactor.

Mist Bioreactor

In this bioreactor, the liquid particles are dispersed in the gas phase using a condenser. This vessel is made up of glass and stainless steel. It consists of both upper and lower lids (Zhang, *et al*., 2009) The bioreactor is vertical in position and consists of a thermoregulation system present at the lower side. Temperature and level sensors are also present on the top. LED jacket, hydraulic spray nozzle and a ring sparger is also integrated inside it (Astron and Hagglun,1984). On the upper side, gas inlet and outlet are present meant for the entrance and exit of gases. A condenser is mounted at the top of fermenter in order to avoid liquid efflux from the fermenter. Vessel is designed on such a way to maintain sterility using autoclaving. Pressure is also regulated inside the fermenter by using an adjustable gas valve (Robinson and Nigam, 1993).

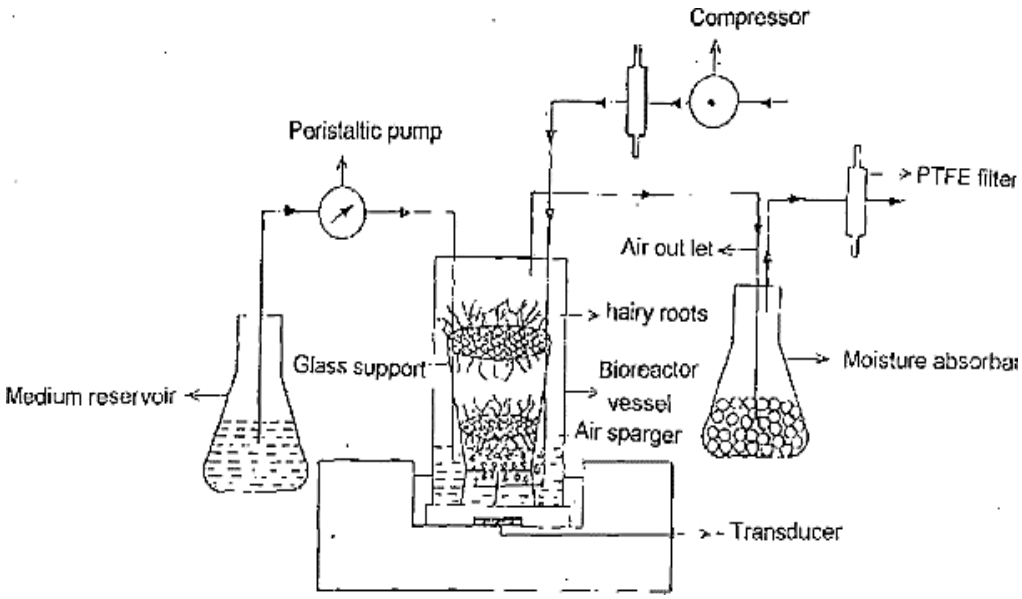

Figure 16: Mist bioreactor.

Advantages of Mist Bioreactor: Low productivity cost. It provides elimination of hydrodynamic stress. High oxygen transfer is maintained (Durand, 2003).

Cyclone column Fermenter

In cyclone column fermenter, circulation of culture occurs across a loop providing aeration, proper mixing and appropriate cultivation of cells. No agitator or stirrer is present as in other fermenters. A pump is present is a large vertical glass column which is involve in recycling the culture from bottom to top (Robinson and Nigam, 1993). A tangential introduction of culture is done from the cyclone head which provides kinetic velocity to spin the culture from the inlet to bottom which is then recirculated with the help of pump. Air is introduced from the bottom of fermenter. A laboratory fermenter has a capacity of 500-1000 ml and can be used for both batch and continuous fermentation (Lee, *et al.*, 2009). Advantages of Cyclone column fermenter: Simple to use. Better operation. Avoid foaming. Growth on the sides of fermenter is prevented (Lee, *et al.*, 2009).

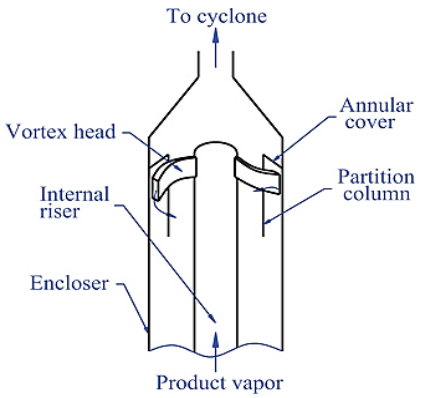

Figure 16: Cyclone column fermentor.

Novel see-saw Bioreactor

This bioreactor is developed for laboratory use. It is mainly used for animal cell cultures. Controlled

conditions are maintained inside the fermenter to maintain culturing (Pal and Tramper, 1998). Aerobic supply of oxygen is important in aerobic fermentation. Proper aeration is maintained by the see saw motion of this fermenter. However, due to the see saw motion of fluid, sheer force may be generated which may damage animal cells (Sam and Biswas,1998).

Design of bioreactor and the optimization of fermenting process is very important in order to scale-up laboratory scale fermentations to the industrial levels for enhanced product production. Further efforts must be made to boost up technology and performance of bioreactors (Saha, *et.al*, 2001). Strategies must be designed to lower cost of fermentation and construction of fermenters no matter which product is being produced (Doebelin, 1998). Novel and innovative industrial products can be developed very easily by establishing a more sustainable industrial production (Chakraborty, A., 2001).

Future Perspectives

Design of bioreactor and the optimization of fermenting process is very important in order to scale-up laboratory scale fermentations to the industrial levels for enhanced product production. Further efforts must be made to boost up technology and performance of bioreactors. Strategies must be designed to lower cost of fermentation and construction of fermenters no matter which product is being produced. Novel and innovative industrial products can be developed very easily by establishing a more sustainable industrial production (Lee, *et al.*, 2009).

CONCLUSION

Fermentations can be made using all types of cells such as animal, plant, mammalian, algae, fungi and bacteria depending upon the design of fermenter designed specifically according the types of cells used to carrying out fermentation. However bacteria, yeast and fungal cells are widely used in industrial fermentations. Fermenters are designed to maximize fermentation process but each provides several advantages as well as some limitation as nothing in nature can be perfect. So fermenters must be selected according to the type of cells being used and the type of product which has to be made.

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