

BIOREACTOR SYSTEM FOR MULTI-STAGE BIOLOGICAL WASTEWATER TREATMENT

FIELD AND BACKGROUND OF THE INVENTION

5 The present invention relates to biological wastewater treatment systems, and more particularly, to a bioreactor system for multi-stage biological wastewater treatment based on spatial microorganisms successions and trophic hydrobionts chains.

10 It is known that a spatially segregated trophic microorganism chain provides conditions at which larger organisms consume smaller ones. Such a spatial microorganism succession forms a basis for purification processes by means of both aerobic and anaerobic destruction of microorganisms. The result of such a succession is an increased efficiency of biochemical treatment and a reduced quantity of surplus biomass. Such purification processes are suitable for both domestic and industrial
15 wastewaters, even those containing high levels of organic and inorganic impurities.

 Characteristically, systems for wastewater treatment by trophic microorganism chains include bioreactors having modular spatial aerobic and anaerobic units. Each bioreactor is provided with a controlled air supply that maintains the oxygen level needed for the activity of the microorganisms and enhances the biomass exchange.

20 Prior art bioreactors suffer from various drawbacks. Trickling filters require a large space, generate secondary pollution including bad odors, and attract flies. Activated sludge processes generate large amounts of biomass that need careful monitoring due to sudden changes in biomass loading and plugging. Rotational bioreactors are more compact, however, they are expensive and prone to mechanical
25 problems.

 It is known that bioreactors using fixed submerged biomass usually perform well at low biomass loadings, but are easily plugged by excessive buildup of biomass, therefore, demanding periodic cleaning or replacing of the submerged biomass. These prior art fixed submerged biomass bioreactors require many bioreactors to keep
30 the loading low to maintain the purification efficiency. Consequently these

wastewater-treating facilities demand frequent monitoring, good control of flow and load, and are expensive to install, operate and maintain.

U.S. Patent No. 4,005,010 to Lunt describes a wastewater treatment system having mesh sacks containing a biological medium. The sacks are apparently
5 designed to hold the microbes while allowing fluids to pass through. The biological medium is prone to clogging over the course of operation.

U.S. Patent No. 4,165,281 to Kuriyama, et al., describes a wastewater treatment system that includes a substrate designed to contain the microorganisms. A plurality of vertically disposed substrates is designed for wastewater to pass
10 therethrough. The likelihood of plugging is greater in this unit than in the Lunt device, due to the orientation of the substrates and to the difficulty in maintaining and/or replacing them.

U.S. Patent No. 4,279,753 to Nielson, et al., describes the arrangement of a plurality of treatment reactors alternating from aerobic to anaerobic action. While
15 Nielson indicates that it is necessary to address plugging problems, the technique for doing so is relatively crude and appears to be less than completely effective.

U.S. Patent No. 4,521,311 to Fuchs, et al., teaches the use of a filtering bed through which the wastewater passes and which includes support bedding to suspend the biological medium. The device has a rather complex recirculation process in order
20 to ensure cleaning of the bedding and the microbes. This device may experience additional kinds of clogging problems, and the disclosed bedding particles are required to go through a costly maintenance operation.

U.S. Patent No. 5,221,470 to McKinney describes a wastewater treatment plant having a final filter made of a sheet of plastic. The sheet of plastic is wrapped about
25 itself so as to form passageways designed for microbe growth. While this design may increase the surface area and, therefore, the dwell time available for microbial action, it is likely that plugging will occur as the passageway fills with dead microbes over a period of time.

In summary, prior-art bioreactor systems for multi-stage biological wastewater
30 treatment are often plagued by inefficiency over a period of operation. When the wastewater to be treated requires the use of a considerable amount of biological mass,

there results a problem of plugging of the mass. As waste solids build up on the surface of the mass, or as microbes ingest the pollutants and die, such solids do not always fall to the bottom of the bioreaction tank. Instead, the solids become trapped at or near the surface of the mass. This plugging or blocking of the mass significantly reduces the pathways by which subsequent pollutants may pass through to underlying active microbes that are located below the surface of the mass. Consequently, the acceleration of pollutant decay caused by microbe ingestion is compromised, and water flow through the mass is reduced and may even be stopped. It is therefore necessary to either build a substantially larger bioreactor unit than would otherwise be required--in order to account for this plugging--or to regularly clean the clogged system.

There is therefore a recognized need for, and it would be highly advantageous to have a bioreactor system for multistage biological wastewater treatment that is robust and efficient, simple to operate, insusceptible to plugging, and inexpensive to install and maintain.

SUMMARY OF THE INVENTION

According to the teachings of the present invention there is provided a multiple stage bioreactor system for microbiological treatment of wastewater, the bioreactor system including: at least one highly-flexible substrate for providing a superficial environment conducive for supporting biomass growth, the substrate including: (a) a large plurality of threads, the threads disposed in a generally longitudinal direction and including a plurality of synthetic filaments, and (b) at least two cross-support elements disposed across and associated with the plurality of threads, so as to provide support for and loosely associate the threads, wherein openings defined by (i) adjacent threads of the threads, and (ii) adjacent cross-support elements of the elements, have an aspect ratio exceeding 50 to 1.

According to further features in the described preferred embodiments, the aspect ratio exceeds 200 to 1.

According to still further features in the described preferred embodiments, the aspect ratio exceeds 500 to 1.

According to still further features in the described preferred embodiments, the aspect ratio exceeds 2000 to 1.

According to still further features in the described preferred embodiments, the length extension of the threads in the substrate is in a range of 80% to 98%.

5 According to still further features in the described preferred embodiments, the length extension of the threads is in a range of 90% to 95%.

According to still further features in the described preferred embodiments, the threads include at least one synthetic material selected from the group consisting of polyamide, polypropylene, and cross-linked polyester.

10 According to still further features in the described preferred embodiments, the at least two cross-support elements are woven elements interwoven with the threads.

According to still further features in the described preferred embodiments, the woven elements include at least one synthetic material selected from the group consisting of polyamide, polypropylene, and cross-linked polyester.

15 According to still further features in the described preferred embodiments, the cross-support elements form an angle, with respect to the threads, in a range of 30° to 90°.

According to another aspect of the present invention there is provided a multiple stage bioreactor system for microbiological treatment of wastewater, the
20 bioreactor system including: at least one substrate for providing a superficial environment conducive for culturation of microbes, the substrate including: (a) a large plurality of threads, the threads disposed in a generally longitudinal direction, and (b) at least two cross-support elements disposed across and associated with the plurality of threads, so as to provide support for and loosely associate the threads,
25 wherein a length extension of the threads in the substrate is in a range of 80% to 98%.

According to yet another aspect of the present invention there is provided a multiple stage bioreactor system for microbiological treatment of wastewater, the bioreactor system including: at least one bioreactor including: (a) a feed inlet for
30 receiving a stream of at least partially-untreated wastewater; (b) a plurality of substrate bundles, each bundle including a plurality of laminar substrates for

supporting biomass growth, each of the substrates having threads including a plurality of synthetic filaments, the substrates being juxtaposed in a substantially parallel manner with respect to each other, within the bioreactor, (c) an air supply manifold for fluidly connecting to an air source, the manifold including a plurality of diffusing
5 elements, for forced rising and diffusion of air, the diffusing elements positioned with respect to the substrate bundles such that the air rises and diffuses through the laminar substrates, and wherein the diffusing elements are further positioned with respect to the plurality of substrates such that the rising of air creates a controlled hydrodynamic circulation within the bioreactor, the controlled hydrodynamic
10 circulation being characterized by a linear velocity range bounded by an upper level that enables biomass to settle on the laminar substrates, and bounded by a lower level that provides a pre-determined minimum level of available oxygen throughout the substrates.

According to further features in the described preferred embodiments, the
15 substrate bundle is disposed between adjacent elements of the diffusing elements, and wherein the diffusing elements are disposed substantially opposite to a large face of the substrates.

According to still further features in the described preferred embodiments, the single substrate bundle includes 2 to 12 of the substrates.

20 According to still further features in the described preferred embodiments, from 3 to 8 of the substrates are juxtaposed between adjacent elements of the diffusing elements.

According to still further features in the described preferred embodiments, from 4 to 7 of the substrates are juxtaposed between adjacent elements of the
25 diffusing elements.

According to still further features in the described preferred embodiments, the distance between the diffusing elements and the substrates is between 10 and 30 cm, so as to achieve the controlled hydrodynamic circulation.

According to still further features in the described preferred embodiments, the
30 distance between the substrates and a bottom of the bioreactor is between 50 and 80 cm, so as to achieve the controlled hydrodynamic circulation.

According to still further features in the described preferred embodiments, the diffusing elements are further positioned with respect to the plurality of substrates such that a major stream of oxygen-containing liquid flows down, through clearances between adjacent substrates of the substrates, towards a bottom of the bioreactor.

5 According to still further features in the described preferred embodiments, the threads are disposed in a generally longitudinal direction, and wherein each of the substrates further includes at least two cross-support elements, disposed across and associated with the plurality of threads, so as to provide support for and loosely associate the threads, and wherein the cross-support elements are positioned so as to
10 effect turbulent flow of the wastewater between the substrates.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail,
15 it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the
20 invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

In the drawings:

Figure 1 shows a multi-stage biological activated bioreactor system for
25 wastewater treatment based on spatial microorganisms successions and trophic hydrobionts chains;

Figure 2a is a side view of a substrate for biomass buildup;

Figure 2b shows a flow regime of liquid within two adjacent substrates;

Figure 2c schematically describes the cross-support elements interwoven with
30 threads of the substrates, and

Figure 3 illustrates the hydrodynamic circulation within a bioreactor, according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

5 The present invention is a bioreactor system for treating wastewater, using fixed submerged substrates for the biomass. The bioreactor system is robust and efficient, simple to operate, and highly insusceptible to plugging.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of
10 construction and the arrangement of the components set forth in the following description or illustrated in the drawing. The invention is capable of other embodiments or of being practiced or carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

15 The principles and operation of the system according to the present invention may be better understood with reference to the drawings and the accompanying description.

Referring now to the drawings, Figure 1 shows a multi-stage biological activated bioreactor system **100** for wastewater treatment based on spatial
20 microorganisms successions and trophic hydrobionts chains. Multi-stage bioreactor system **100** includes a plurality (six are shown) of associated bioreactors **40**.

Air supply header **12**, connected to an air supply source (not shown in the drawing) supplies the oxygen required in each bioreactor **40** by secondary air lines **14** and check valves **16**. These air flows are controlled according to the oxygen demand
25 in each specific bioreactor **40**. Secondary air lines **14** deliver air to manifolds **20**, disposed near or at a bottom **18** of each bioreactor **40**. Manifolds **20** divide the air supply into yet smaller streams, from which emerge upward-flowing air streams via diffusing elements **22** (shown in Figure 3).

Generally, systems that employ such diffusing elements are superior in treating
30 ability and treating efficiency to a conventional fixed-bed process. Fixed-bed processes, as disclosed, for example, in Sadao Kojima, Yosui To Haisui, Industrial

Water and Waste Water, 14, p. 960, (1972) and Y. Maeda, Journal of Fermentation Technology, 53, p. 875 (1975), suffer from excessive clogging of biomass on the supporting media or substrates and from excessive sloughing of falling biomass. Consequently, prior art systems deal mainly with this problem and do not deal with
5 improving the hydrodynamics of the bioreactors.

In sharp contrast to the prior art, one aspect of the present invention focuses on, and appreciably improves, the hydrodynamics of bioreactor 40. Referring now to Figure 3, air diffused from diffusing elements 22 rises at a linear velocity so as to produce, in bioreactor 40, an "air-lift" effect in which the liquid is carried upwards by
10 the rising air bubbles.

Hydrodynamic circulation within bioreactor 40 is achieved by positioning each diffusing element 22 with respect to substrates 10 such that a major stream of liquid flows up from diffusing element 22 between two substrates 10 that immediately surround diffusing element 22. This causes a hydrodynamic circulation 25 around the
15 top of substrates 10, and down, through the clearances between substrates 10, and through a middle region of substrate bundle 90, towards bottom 18 of bioreactor 40. This hydrodynamic pattern can be advantageously controlled such that a predetermined minimum level of oxygen is delivered throughout substrates 10, and such that the linear velocity of liquid flowing up from diffusing element 22 is sufficiently
20 low to avoid turbulence and to allow biomass to settle so as to achieve optimal buildup on substrates 10.

It has been found that in order to achieve the inventive hydrodynamic circulation pattern described hereinabove, the number of substrates 10 between adjacent diffusing elements 22 should be in the range of 2 to 14, preferably in the
25 range of 2 to 12, more preferably in the range of 3 to 8, and most preferably, 5 or 6.

Additionally, as will be readily apparent to one skilled in the art, the circulation is influenced and controlled by the number of diffusing elements 22, the distance between them, the distance between diffusing elements 22 and the lower edge of substrates 10, the number of substrates 10 in bioreactors 40, the distance between
30 adjacent substrates 10, and wastewater and air flows.

Multi-stage treatment system **100** is continuously fed with wastewater, or partially-treated wastewater, via inlet **26**, which is disposed in an upper part of a first sidewall **28** of system **100**. The effluent from the first bioreactor of bioreactors **40** overflows into an adjacent bioreactor through discharge opening **30**, located at an opposite side of the first bioreactor, with respect to inlet **26**. Similarly, the effluent of the second bioreactor of bioreactors **40** overflows to the third bioreactor of bioreactors **40** through discharge opening **32**. Discharge openings **30** and **32** (as well as the discharge openings of all other bioreactors **40**) are preferably disposed with respect to one another so as to minimize short-circuiting phenomena within each bioreactor **40**.

The treated water produced is discharged from system **100** via outlet **44**, which is disposed in an upper part of a second sidewall **46**.

Referring now to Figure 2a, Figure 2a is a side view of a substrate **10** for biomass buildup. Substrate **10** is a loose, laminar, synthetic filter material for supporting biomass growth. Substrate **10**, which normally has a height of 1.5 to 4.5 m, a width of 1 to 2 m, and a thickness of only 2 to 10 mm, includes longitudinal threads **50**, having a linear density of 100 to 500 dtex, and preferably 200 to 400 dtex. Each thread **50** is typically made up of about 200 to about 500 filaments that provide an enhanced surface area for biomass growth.

Threads **50** are associated and held together by a small number of cross-support elements **52**, typically disposed in transverse fashion with respect to threads **50**. Each cross-support element **52** is preferably a strip having a width of 2 to 10 cm, and is advantageously formed of interwoven cross threads **80** as shown in Figure 2c.

The distance between cross-support elements **52** is at least 20 cm, and preferably, 20 to 50 cm.

In prior-art mesh substrates, the ratio of the length to the width of the mesh openings is 1:1 to 1:3 and more typically, about 1:1. By sharp contrast, the ratio of the length to the width of the openings formed by threads **50** and strips **52**, according to the present invention, is greater than 1:50, preferably greater than 1:200, more preferably, greater than 1:500 and even more preferably, greater than 1:2000. Inventive substrate **10** is thus extremely flexible and has large openings with respect

to prior-art substrates. Consequently, the biomass has much less firm support, and biomass build-up – which leads to plugging -- tends to significantly decrease.

As used herein in the specification and in the claims section that follows, the term "aspect ratio" refers to a ratio between the length and the width of an opening
5 formed by adjacent threads **50** and adjacent cross-support elements **52** in a substrate.

Cross-support elements **52** are advantageously thicker than threads **50**, so as to restrict water flow **74** between juxtaposed substrates **10**, as shown in Figure 2b. Thus, instead of the laminar flow characteristic of prior-art systems, the inventive system is characterized by a turbulent flow regime **70** between substrates **10**, which
10 enhances the oxygen supply needed for biomass growth.

The length extension of the vertical threads **50** in substrate **10** has also been found to be of paramount importance in attaining optimal biomass build-up. As used herein in the specification and in the claims section that follows, the term "length extension" refers to a ratio, expressed in percent, between the length of a section of a
15 substrate between adjacent cross-support elements (**L** in Figure 2a), and the average length of the threads forming that section. By way of example, in a substrate in which the threads are associated by cross-support elements at the top end and at the bottom end of the substrate, and in which (1) the substrate length **L** is 0.45 meters, and (2) the average length of the threads is 0.5 meters, the length extension would be
20 equal to $100 \times 0.45 / 0.5$, or 90%.

The length extension of substrate **10** typically exceeds 80%, preferably lies within a range of 85% to 98%, more preferably, within a range of 90% to 95%, and most preferably, within a range of 92% and 95%. Within these narrow ranges of the length extension, adjacent threads **50** have a suitable flexibility, with respect to one
25 another, so as to enable controlled biomass buildup on substrates **10**.

Consequently, sloughing is greatly reduced and sloughing of falling biomass as a result of excessive biomass buildup is avoided, as well as excessive biomass loading of down stream bioreactors due to excessive biomass carryover as sloughing from former bioreactors of the multi-stage system.

Threads **50** and cross threads **80** are preferably made of synthetic materials such
30 as polyamide, polypropylene, cross-linked polyester, or any combination thereof.

These water-resistant materials enable long-term fabric durability in the aqueous medium, while their low shrinkage properties allow the initial (i.e., at the time of installation) fabric tension of substrates **10** to be preserved.

Typical purification efficiencies of a multi-stage biological activated
 5 wastewater treatment system of the present invention are provided in Table 1.

Table1: Purification Efficiency of A Multi-Stage Biological Activated Waste Water Treatment	
Biological Oxygen Demand (BOD)	97% - 99.5%
Chemical Oxygen Demand (COD)	85% - 95%
Total Suspended Solids (TSS)	95% - 97%
NH ₄ ⁺	90% - 99%
Oil & Grease	95% - 100%
Detergents	80% - 95%

Although the invention has been described in conjunction with specific
 10 embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims. All publications, patents and patent applications mentioned in this specification, including U.S. Patent Nos. 4,005,010,
 15 4,165,281, 4,279,753, 4,521,311, and 5,221,470, are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such
 20 reference is available as prior art to the present invention.

WHAT IS CLAIMED IS:

1. A multiple stage bioreactor system for microbiological treatment of wastewater, the bioreactor system comprising:

at least one highly-flexible substrate for providing a superficial environment conducive for supporting biomass growth, said substrate including:

- (a) a large plurality of threads, said threads disposed in a generally longitudinal direction and including a plurality of synthetic filaments, and
- (b) at least two cross-support elements disposed across and associated with said plurality of threads, so as to provide support for and loosely associate said threads,

wherein openings defined by

- (i) adjacent threads of said threads, and
- (ii) adjacent cross-support elements of said elements,

have an aspect ratio exceeding 50 to 1.

2. The bioreactor system of claim 1, wherein said aspect ratio exceeds 200 to 1.

3. The bioreactor system of claim 1, wherein said aspect ratio exceeds 500 to 1.

4. The bioreactor system of claim 2, wherein said aspect ratio exceeds 2000 to 1.

5. The bioreactor system of claim 1, wherein a length extension of said threads in said substrate is in a range of 80% to 98%.

6. The bioreactor system of claim 5, wherein said length extension of said threads is in a range of 90% to 95%.

7. The bioreactor system of claim 1, wherein said threads include at least one synthetic material selected from the group consisting of polyamide, polypropylene, and cross-linked polyester.

8. The bioreactor system of claim 1, wherein said at least two cross-support elements are woven elements interwoven with said threads.
9. The bioreactor system of claim 8, wherein said woven elements include at least one synthetic material selected from the group consisting of polyamide, polypropylene, and cross-linked polyester.
10. The bioreactor system of claim 1, wherein said cross-support elements form an angle, with respect to said threads, in a range of 30° to 90°.
11. A multiple stage bioreactor system for microbiological treatment of wastewater, the bioreactor system comprising:
at least one highly-flexible substrate for providing a superficial environment conducive for culturation of microbes, said substrate including:
 - (a) a large plurality of threads, said threads disposed in a generally longitudinal direction, and
 - (b) at least two cross-support elements disposed across and associated with said plurality of threads, so as to provide support for and loosely associate said threads,wherein a length extension of said threads in said substrate is in a range of 80% to 98%.
12. The bioreactor system of claim 11, wherein said length extension is in a range of 85% to 95%.
13. The bioreactor system of claim 11, wherein said length extension is in a range of 90% to 95%.

14. The bioreactor system of claim 12, wherein openings defined by:
- (i) adjacent threads of said threads and
 - (ii) adjacent cross-support elements of said elements,
- have an aspect ratio exceeding 200 to 1.
15. The bioreactor system of claim 14, wherein said aspect ratio exceeds 500 to 1.
16. The bioreactor system of claim 11, wherein said threads include at least one synthetic material selected from the group consisting of polyamide, polypropylene, and cross-linked polyester.
17. A multiple stage bioreactor system for microbiological treatment of wastewater, the bioreactor system comprising:
- at least one bioreactor including:
- (a) a feed inlet for receiving a stream of at least partially-untreated wastewater;
 - (b) a plurality of substrate bundles, each bundle of said substrate bundles including a plurality of laminar, highly-flexible substrates for supporting biomass growth, each of said substrates having threads including a plurality of synthetic filaments, said substrates being juxtaposed in a substantially parallel manner with respect to each other, within said bioreactor,
 - (c) an air supply manifold for fluidly connecting to an air source, said manifold including a plurality of diffusing elements, for forced rising and diffusion of air, said diffusing elements positioned with respect to said substrate bundles such that said air rises and diffuses through said laminar substrates,
- and wherein said diffusing elements are further positioned with respect to said plurality of substrates such that said rising of air creates a controlled hydrodynamic circulation within said bioreactor, and
- wherein said controlled hydrodynamic circulation is characterized by a linear

velocity range bounded by an upper level that enables biomass to settle on said laminar substrates, and bounded by a lower level that provides a pre-determined minimum level of available oxygen throughout said substrates.

18. The bioreactor system of claim 17, wherein a bundle of said bundles is disposed between adjacent elements of said diffusing elements, and wherein said diffusing elements are disposed substantially opposite to a large face of said substrates.

19. The bioreactor system of claim 17, wherein said single bundle includes 2 to 12 of said substrates.

20. The bioreactor system of claim 17, wherein from 3 to 8 of said substrates are juxtaposed between adjacent elements of said diffusing elements.

21. The bioreactor system of claim 17, wherein from 4 to 7 of said substrates are juxtaposed between adjacent elements of said diffusing elements.

22. The bioreactor system of claim 17, wherein a distance between said diffusing elements and said substrates is between 10 and 30 cm, so as to achieve said controlled hydrodynamic circulation.

23. The bioreactor system of claim 17, wherein a distance between said substrates and a bottom of said bioreactor is between 50 and 80 cm, so as to achieve said controlled hydrodynamic circulation.

24. The bioreactor system of claim 17, wherein said diffusing elements are further positioned with respect to said plurality of substrates such that a major stream of oxygen-containing liquid flows down, through clearances between adjacent substrates of said substrates, towards a bottom of said bioreactor.

25. The bioreactor system of claim 17, wherein said threads are disposed in a generally longitudinal direction, and wherein each of said substrates further includes at least two cross-support elements, disposed across and associated with said plurality of threads, so as to provide support for and loosely associate said threads, and wherein said cross-support elements are positioned so as to effect turbulent flow of the wastewater between said substrates.