Seoul National University

457.621.001

Biological Processes in Environmental Engineering

FINAL EXAMINATION - Solutions

TIME ALLOWED: 90 MINUTES

December 03, 2020

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1. Students may use two sheets of double-sided, A4-sized notes prepared in their own handwriting. Mechanical or electronic reproduction of any notes are not allowed.

2. Students should bring their own calculator which is not pre-programmed with formulae from the class.

3. Be aware that a student who cheated during the exam will get no credits.

4. Make sure your answers include units if appropriate. Watch your units! Prepare your answers in a logical, easy-to-follow format.

5. This exam contains 6 questions. The total points is 100.

1. Mark true or false (T/F) for the following statements.

Note: +1.5 points for correct answers, -1.5 points for incorrect answers, and 0 point if you choose not to answer.

1) Classifying bacterial species into Gram positive and Gram negative bacteria is a way of taxonomic classification.

Answer) T

2) Under a sufficiently high substrate concentration, the enzyme reaction is not significantly affected by a competitive inhibitor.

Answer) T

3) Bacterial cells are generally assumed to be 100% biodegradable.

Answer) F

4) Fermentation of glucose to produce ethanol results in more than 50% loss in COD.

Answer) F

5) Pyruvate (CH_3COCOO^-) is the major energy storage material in bacterial cells.

Answer) F

6) At the same hydraulic retention time (HRT) value, a PFR (plug flow reactor) will show higher removal efficiency than a CSTR (continuously stirred tank reactor) for a chemical that undergoes first-order degradation reaction in the reactors.

Answer) T

7) A/O process is generally applied for the biological treatment of nitrogen and phosphorus.

Answer) F

8) Denitrification mediated by heterotrophs is an alkalinity-producing process.

Answer) T

9) Filamentous organisms generally show better settleability than phosphate accumulating

organisms (PAOs).

Answer) F

10) Moving bed biofilm reactors (MBBRs) are generally operated at a higher volumetric organic loading rate (OLR) than conventional activated sludge.

Answer) T

2. Define the following biological processes.

1) Bacterial conjugation (5 points)

Answer)

A horizontal gene process through which genetic materials transferred between bacterial cells by direct cell-to-cell contact or by a bridge-like connection between two cells

2) Simultaneous nitrification and denitrification (5 points)

Answer)

Occurrence of nitrification and denitrification in the same reactor which is accomplished by the presence of aerobic and anoxic conditions at different parts of a reactor, for example, at different parts of a floc, granule, or biofilm

3) Reductive dechlorination (5 points)

Answer)

Replacement of chlorine substituents by hydrogen mediated by microorganisms via utilization of chlorinated organic compounds as an electron acceptor

4) Cometabolism (5 points)

Answer)

Transformation of a compound by an organism that is unable to use the compound as a carbon or energy source, which occurs because an enzyme produced by the organism for catalyzing a carbon or energy source is also capable of degrading the target compound

3. Answer the following questions.

1) Briefly describe strategies to form microbial granules that can be used to operate an aerobic granular sludge process. (6 points)

Answer)

Fast-famine regime: expose microorganisms to alternating condition of presence/absence of organic matter

Hydrodynamic shear force: impose high shear force to improve physical integrity of granules

Short settling time: provide selection power for granules against flocs

2) Discuss the opportunities and challenges of adopting anaerobic biological processes for mainstream domestic wastewater treatment. (6 points)

Answer)

Opportunities

- can recover energy in the form of biogas from wastewater

- lower sludge production rate

Challenges

- poor effluent quality

- *odor problem*

- *operational difficulty and high sensitivity to toxic chemicals, environmental conditions, etc.*

3) Describe the fate of a highly recalcitrant, non-volatile, and water-insoluble compound during a typical domestic wastewater treatment process. (6 points)

Answer)

The compound enters the process mostly in the form of particle-associated form; a portion of the initial load is removed from water in the form of primary sludge at the primary clarifier and a large portion is removed in the form of secondary sludge at the secondary clarifier; very little amount remained in the final effluent; the compound is neither transformed nor volatilized into the atmosphere, though, during the process

4. Write a balanced cell formation half reaction (R_c) using CO_2 as a carbon source and NO_3^- as a nitrogen source. Use $C_5H_7O_2N$ as cell formula. Provide your final answer in an electron-equivalent form. (12 points)

Answer)

Step 1: $CO_2 = C_5H_7O_2N$

Step 2: $CO_2 + NO_3^- + H_2O + e^- = C_5H_7O_2N$

Step 3: $5CO_2 + NO_3^- + H_2O + e^- = C_5H_7O_2N$

Step 4: $5CO_2 + NO_3^- + e^- = C_5H_7O_2N + 11H_2O$

Step 5: $5CO_2 + NO_3^- + 29H^+ + e^- = C_5H_7O_2N + 11H_2O$

Step 6: $5CO_2 + NO_3^- + 29H^+ + 28e^- = C_5H_7O_2N + 11H_2O$

Step 7: $\frac{5}{28}CO_2 + \frac{1}{28}NO_3^- + \frac{29}{28}H^+ + e^- = \frac{1}{28}C_5H_7O_2N + \frac{11}{28}H_2O$

5. Write up balanced energy reactions for the following biological processes. Pick up half reactions provided in Appendix to build up the reactions. Show which half reactions you select and how the half reactions are combined. Provide your final answer in an electron-equivalent form.

1) Glucose fermentation to lactate (5 points)

Answer)

(O-7): $\frac{1}{4}CO_2 + H^+ + e^- = \frac{1}{24}C_6H_{12}O_6 + \frac{1}{4}H_2O$

(O-11): $\frac{1}{6}CO_2 + \frac{1}{12}HCO_3^- + H^+ + e^- = \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{3}H_2O$

(O-11) - (O-7): $\frac{1}{24}C_6H_{12}O_6 + \frac{1}{12}HCO_3^- = \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{12}H_2O + \frac{1}{12}CO_2$

by eliminating the inorganic carbon species that appear at both sides,

$$\frac{1}{24}C_6H_{12}O_6 + \frac{1}{12}H_2O = \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{12}H^+$$

2) Anammox (5 points)

Answer)

(I-3): $\frac{1}{6}N_2 + \frac{4}{3}H^+ + e^- = \frac{1}{3}NH_4^+$

(I-8): $\frac{1}{3}NO_2^- + \frac{4}{3}H^+ + e^- = \frac{1}{6}N_2 + \frac{2}{3}H_2O$

(I-8) - (I-3): $\frac{1}{3}NH_4^+ + \frac{1}{3}NO_2^- = \frac{1}{3}N_2 + \frac{2}{3}H_2O$

3) Hydrogenotrophic methanogenesis (5 points)

Answer)

(I-5): $H^{+} + e^{-} = \frac{1}{2}H_2$

(O-12): $\frac{1}{8}CO_2 + H^{+} + e^{-} = \frac{1}{8}CH_4 + \frac{1}{4}H_2O$

(O-12) - (I-5): $\frac{1}{2}H_2 + \frac{1}{8}CO_2 = \frac{1}{8}CH_4 + \frac{1}{4}H_2O$

6. Following table lists parameters for a laboratory chemostat (CSTR) in operation for aerobic treatment of wastewater. Using the parameter values, answer the questions below.

Item	**Symbol**	**Value**
Flowrate	Q^0	20 L/d
Influent soluble BOD	S^0	150 mg BOD_L/L
Influent particulate BOD	S_p^0	0 mg BOD_L/L
Influent active biomass	X_a^0	0 mg VSS/L
Influent nonbiodegradable VSS (nbVSS)	X_i^0	20 mg VSS/L
Influent dissolved oxygen (DO) concentration	$S_{O_2}^0$	1.5 mg O_2/L
Chemostat volume	V	50 L
Maximum specific substrate utilization rate	$\hat{q}$	7.5 mg BOD_L/mg VSS-d
Half saturation coefficient	K	10 mg BOD_L/L
Decay coefficient	b	0.10 d^{-1}
Biodegradable fraction of biomass	f_d	0.80
True yield	Y	0.50 mg VSS/mg BOD_L
First-order hydrolysis rate constant	k_{hyd}	0.20 d^{-1}
Effluent dissolved oxygen (DO) concentration	S_{O_2}	1.5 mg O_2/L

Notes:

i) Neglect the production of soluble microbial products.

ii) Assume that all forms of VSS in the aeration tank can be represented as $C_5H_7O_2N$.

1) The soluble BOD_L value of the effluent (3 points)

Answer)

Hydraulic retention time $\theta = \dfrac{V}{Q} = \dfrac{50\ L}{20\ L/d} = 2.5\ d$

$$S = K\frac{1+b\theta}{Y\hat{q}\theta-(1+b\theta)} = 10 \cdot \frac{1+0.10 \cdot 2.5}{0.50 \cdot 7.5 \cdot 2.5-(1+0.10 \cdot 2.5)} = 1.54\ mg\ BOD_L/L$$

2) Safety factor (SF), which is defined as

$$SF = \frac{\theta_x}{\theta_x^{\min}}$$

where θ_x = solids retention time (SRT) of the system

$\theta_x^{\min}$ = the SRT value above which value should be maintained to prevent washout

(4 points)

Answer)

Since $\theta_x = \theta$,

$\theta_x = 2.5\ d$

$$\theta_x^{\min} = \frac{K+S^0}{S^0(Y\hat{q}-b)-bK} = \frac{10+150}{150 \cdot (0.50 \cdot 7.5-0.10)-0.10 \cdot 10} = 0.293\ d$$

$$SF = \frac{\theta_x}{\theta_x^{\min}} = \frac{2.5\ d}{0.293\ d} = 8.53$$

3) The total BOD_L value of the effluent (7 points)

Answer)

$$X_a = \frac{Y(S^0-S)}{1+b\theta} = \frac{0.50 \cdot (150-1.54)}{1+0.10 \cdot 2.5} = 59.4\ mg\ VSS/L$$

Total BOD_L *in the effluent* = $S + 1.42 f_d X_a = 1.54 + 1.42 \cdot 0.8 \cdot 59.4 = 69.0\ mg\ BOD_L/L$

4) The amount of oxygen that should be provided into the chemostat (in g O_2/d) (6 points)

Answer)

$$R_a = \gamma_a\left[Q^0\left(S^0 + 1.42X_v^0\right) - Q\left(S + SMP + 1.42X_v\right)\right]$$

$$X_v = X_i^0 + X_a\{1 + \left(1 - f_d\right)b\theta\} = 20 + 59.4 \cdot \{1 + (1 - 0.80) \cdot 0.10 \cdot 2.5\} = 82.4\ mg\ VSS/L$$

$$R_a = 1 \cdot [20 \cdot (150 + 1.42 \cdot 20) - 20 \cdot (1.54 + 1.42 \cdot 82.4)] = 1200\ mg/d = 1.2\ g/d$$

Appendix. List of half reactions

Inorganic half-reactions and their Gibb's free energy at pH = 7.0

Textbook Table 2.1

Reaction Number	Reduced-oxidized Compounds	Half-reaction		$\Delta G^{0'}$ (kJ/e- eq)
I-1	Ammonium-nitrate	$\frac{1}{8}NO_3^- + \frac{5}{4}H^+ + e^-$	$= \frac{1}{8}NH_4^+ + \frac{3}{8}H_2O$	-35.11
I-2	Ammonium-nitrite	$\frac{1}{6}NO_2^- + \frac{4}{3}H^+ + e^-$	$= \frac{1}{6}NH_4^+ + \frac{1}{3}H_2O$	-32.93
I-3	Ammonium-Nitrogen	$\frac{1}{6}N_2 + \frac{4}{3}H^+ + e^-$	$= \frac{1}{3}NH_4^+$	26.70
I-4	Ferrous-Ferric	$Fe^{3+} + e^-$	$= Fe^{2+}$	-74.27
I-5	Hydrogen-H^+	$H^+ + e^-$	$= \frac{1}{2}H_2$	39.87
I-6	Nitrite-Nitrate	$\frac{1}{2}NO_3^- + H^+ + e^-$	$= \frac{1}{2}NO_2^- + \frac{1}{2}H_2O$	-41.65
I-7	Nitrogen-Nitrate	$\frac{1}{5}NO_3^- + \frac{6}{5}H^+ + e^-$	$= \frac{1}{10}N_2 + \frac{3}{5}H_2O$	-72.20
I-8	Nitrogen-Nitrite	$\frac{1}{3}NO_2^- + \frac{4}{3}H^+ + e^-$	$= \frac{1}{6}N_2 + \frac{2}{3}H_2O$	-92.56
I-9	Sulfide-Sulfate	$\frac{1}{8}SO_4^{2-} + \frac{19}{16}H^+ + e^-$	$= \frac{1}{16}H_2S + \frac{1}{16}HS^- + \frac{1}{2}H_2O$	20.85
I-10	Sulfide-Sulfite	$\frac{1}{6}SO_3^{2-} + \frac{5}{4}H^+ + e^-$	$= \frac{1}{12}H_2S + \frac{1}{12}HS^- + \frac{1}{2}H_2O$	11.03
I-11	Sulfite-Sulfate	$\frac{1}{2}SO_4^{2-} + H^+ + e^-$	$= \frac{1}{2}SO_3^{2-} + \frac{1}{2}H_2O$	50.30
I-12	Sulfur-Sulfate	$\frac{1}{6}SO_4^{2-} + \frac{4}{3}H^+ + e^-$	$= \frac{1}{6}S + \frac{3}{2}H_2O$	19.15
I-13	Thiosulfate-Sulfate	$\frac{1}{4}SO_4^{2-} + \frac{5}{4}H^+ + e^-$	$= \frac{1}{8}S_2O_3^{2-} + \frac{5}{8}H_2O$	23.58
I-14	Water-Oxygen	$\frac{1}{4}O_2 + H^+ + e^-$	$= \frac{1}{2}H_2O$	-78.72

Organic half-reactions and their Gibb's free energy at pH = 7.0

Textbook Table 2.2

Reaction Number	Reduced Compounds	Half-reaction		ΔG$^{0'}$ (kJ/e$^-$ eq)
O-1	Acetate	$\frac{1}{8}CO_2 + \frac{1}{8}HCO_3^- + H^+ + e^-$	$= \frac{1}{8}CH_3COO^- + \frac{3}{8}H_2O$	27.40
O-2	Alanine	$\frac{1}{6}CO_2 + \frac{1}{12}HCO_3^- + \frac{1}{12}NH_4^+ + \frac{11}{12}H^+ + e^-$	$= \frac{1}{12}CH_3CHNH_2COO^- + \frac{5}{12}H_2O$	31.37
O-3	Benzoate	$\frac{1}{5}CO_2 + \frac{1}{30}HCO_3^- + H^+ + e^-$	$= \frac{1}{30}C_6H_5COO^- + \frac{13}{30}H_2O$	27.34
O-4	Citrate	$\frac{1}{6}CO_2 + \frac{1}{6}HCO_3^- + H^+ + e^-$	$= \frac{1}{18}(COO^-)CH_2COH(COO^-)CH_2COO^- + \frac{4}{9}H_2O$	33.08
O-5	Ethanol	$\frac{1}{6}CO_2 + H^+ + e^-$	$= \frac{1}{12}CH_3CH_2OH + \frac{1}{4}H_2O$	31.18
O-6	Formate	$\frac{1}{2}HCO_3^- + H^+ + e^-$	$= \frac{1}{2}HCOO^- + \frac{1}{2}H_2O$	39.19
O-7	Glucose	$\frac{1}{4}CO_2 + H^+ + e^-$	$= \frac{1}{24}C_6H_{12}O_6 + \frac{1}{4}H_2O$	41.35
O-8	Glutamate	$\frac{1}{6}CO_2 + \frac{1}{9}HCO_3^- + \frac{1}{18}NH_4^+ + H^+ + e^-$	$= \frac{1}{18}COOHCH_2CH_2CHNH_2COO^- + \frac{4}{9}H_2O$	30.93
O-9	Glycerol	$\frac{3}{14}CO_2 + H^+ + e^-$	$= \frac{1}{14}CH_2OHCHOHCH_2OH + \frac{3}{14}H_2O$	38.88
O-10	Glycine	$\frac{1}{6}CO_2 + \frac{1}{6}HCO_3^- + \frac{1}{6}NH_4^+ + H^+ + e^-$	$= \frac{1}{6}CH_2NH_2COOH + \frac{1}{2}H_2O$	39.80
O-11	Lactate	$\frac{1}{6}CO_2 + \frac{1}{12}HCO_3^- + H^+ + e^-$	$= \frac{1}{12}CH_3CHOHCOO^- + \frac{1}{3}H_2O$	32.29
O-12	Methane	$\frac{1}{8}CO_2 + H^+ + e^-$	$= \frac{1}{8}CH_4 + \frac{1}{4}H_2O$	23.53
O-13	Methanol	$\frac{1}{6}CO_2 + H^+ + e^-$	$= \frac{1}{6}CH_3OH + \frac{1}{6}H_2O$	36.84
O-14	Palmitate	$\frac{15}{19}CO_2 + \frac{1}{92}HCO_3^- + H^+ + e^-$	$= \frac{1}{92}CH_3(CH_2)_{14}COO^- + \frac{31}{92}H_2O$	27.26
O-15	Propionate	$\frac{1}{7}CO_2 + \frac{1}{14}HCO_3^- + H^+ + e^-$	$= \frac{1}{14}CH_3CH_2COO^- + \frac{5}{14}H_2O$	27.63
O-16	Pyruvate	$\frac{1}{5}CO_2 + \frac{1}{10}HCO_3^- + H^+ + e^-$	$= \frac{1}{10}CH_3COCOO^- + \frac{2}{5}H_2O$	35.09
O-17	Succinate	$\frac{1}{7}CO_2 + \frac{1}{7}HCO_3^- + H^+ + e^-$	$= \frac{1}{14}(CH_2)_2(COO^-)_2 + \frac{3}{7}H_2O$	29.09
O-18	Domestic Wastewater	$\frac{9}{50}CO_2 + \frac{1}{50}HCO_3^- + \frac{1}{50}NH_4^+ + H^+ + e^-$	$= \frac{1}{50}C_{10}H_{19}O_3N + \frac{9}{25}H_2O$	*
O-19	Custom Organic	$\frac{(n-c)}{d}CO_2 + \frac{c}{d}HCO_3^- + \frac{c}{d}NH_4^+ + H^+ + e^-$	$= \frac{1}{d}C_nH_aO_bN_c + \frac{2n-b+c}{d}H_2O$ where, $d = 4n + a - 2b - 3c$	*
O-20	Cell Synthesis	$\frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + H^+ + e^-$	$= \frac{1}{20}C_5H_7O_2N + \frac{9}{20}H_2O$	*

* Equations O-18 to O-20 do not have ΔG$^{0'}$ values because the reduced species is not chemically defined.