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Earthworm's gut as reactor in vermicomposting process: A mini review

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Abstract- This review investigates earthworms as reactors towards the development of designer earthworms for the decomposition of complex polymeric structures. Unit operation aspects pertaining to vermicomposting is least addressed or cited in literature, while a lack of models employing worms as composting agents recognizable as biological reactors is quite apparent. The process of isolation of complex macromolecular structures such as protein is also cumbersome and presents inaccuracies. This could be done by studying the effect of various feed sources in different ratios based on the adherence to reactor kinetics and vermicast nutrient compositions. Experimental data would reveal if reactor kinetics are applicable to the earthworms by assessing effect of various food sources and food source mixes at various ratios on vermicast nutrient compositions. Outcome will include extension of reactor kinetics in predicting vermicompostability, which is potentially beneficial to botanists, agriculturalists, environmentalists and biologists by reducing research time and increasing research success rates via relationships derived.

Index Terms- reactor, earthworm gut, vermicomposting, vermicast

I. Introduction

Vermicomposting is defined as a bio-oxidative process in which detritivorous earthworms interact with microorganisms and other fauna within the decomposer community, accelerating the stabilisation of organic matter and greatly modifying its physical and biochemical properties [1]. Vermitechnology refers to methods, processes and designs that relate to vermicomposting. It's an anaerobic process of organic materials which involves wastes, microbes, moisture, oxygen and many environmental factors. When the moisture content and oxygen concentration are brought to a suitable level, microbial activity increases. In addition to oxygen and water, microorganisms require a source of carbon, macronutrients such as N, P, and K, micronutrients, and certain amounts of trace elements for their normal growth and reproduction. These requirements are provided by the organic waste materials. By using the organic matter as a food source the microorganisms reproduce rapidly and release carbon dioxide, water, some organic products, and energy. Some of this energy produced is consumed during the metabolism processes with the remainder released as heat. Although microorganisms are responsible for the biochemical degradation of organic matter in the vermicomposting process, earthworms are important in conditioning the substrate and promoting microbial activity.

Generally, the unit operation aspect pertaining to the technology is least addressed or cited in literature, while a lack of models employing worms as composting agents recognizable as biological reactors is quite apparent. Difficulties in extracting proteins from substrates poses yet another constraint to researchers who intend to study the effects of various forms of these macromolecular structures and their effect on vermicomposting or absorption potentials in worm cast. Most studies on composting using earthworms are typically small-scaled, with reactors centered on containers that contain suitable beddings (mostly waste mixtures) and [2]. Organic wastes from sewage sludge, paper industry waste, urban residues, food and animal waste, and horticultural residues from cultivars have been successfully managed by vermicomposting producing vermicomposts that contain nutrients that are readily taken by plants [1]. The emphasis is rarely on the worm as a reactor. Earthworms are considered as natural reactors since they redesign the physical structure of the soil environment by ingesting litter and soil particles by depositing casts on the soil surface [3]. The benefits of earthworm usage to aid composting are many; their activity determine and are a consequence of soil or substrate characteristics, formation and development via physical, chemical and biological effects [4], [5]. Their casts have tremendous potential and applications, including as ruminant feed modifiers [6] and fish pond fertilizers [7].

Earthworms are capable of disengaging barriers that conventionally immobilize organic matter, including complex proteins and phenolics [5]; they further stimulate and increase biological activity by fragmentation and ingestion of organic matter; this increases the surface area exposed to microorganisms [5]. Lack of understanding of digestive kinetics may, however, lead to poor cast management which result in adverse effects; earthworms have been shown to drive greenhouse gasses via vermicasts, particularly nitrous oxide (N_2O) [8]. Therefore, a thorough comprehension of the worm itself as a reactor and aspects pertaining to the kinetics need addressing to properly assess their effectiveness. The quality of ingested of food, that may include leaf litter, manure, soil organic matter, live or dead roots and root exudates, leachates, organisms, etc., together with various biotic and abiotic factors, affect earthworms and will ascertain the structure of earthworm communities and media they inhabit [5]. The passage of food resources, or substrates, through the worm gut is an important consideration. This involves mechanical action and begins with the process of ingestion at the anterior end, followed by its conveyance via the worm gut right on to the posterior end. The process consummates with egestion of worm-casts, and involves the secretion of various enzymes and mucus within the worm gut and the decomposition and digestion of ingested substrates either directly or with the aid of either resident or ingested microorganisms, [9], [10], [5].

II. CHEMICAL REACTORS AND ITS TYPES

Chemical reactors, which are the containers in which chemical reactions occur, are chiefly characterized by (a) the time variation of the reactant input and (b) the mixing pattern of reactants within the reactor. Based on the time variation of the reactant input, reactors can be classified as batch, semi-batch or continuous-flow types. Continuous-Flow Reactors can further be classified into Continuous Stirred-Tank Reactors and Plug-flow Reactors based on the mixing pattern of the reactants within the reactor [11]. In a Batch reactor, reactants are processed in batches and the contents are perfectly mixed. The concentration of any reactant is spatially uniform but changes with time. This process produces high conversions (digestibilities) if the reactant is left in the reactor for long periods of time. But, because the production' process is discontinuous and an idle period exists between each batch processing, the overall efficiency is low. In Continuous-Stirred Tank Reactor (CSTR), reactants are continuously introduced and the products and unreacted reactants continuously removed. The contents are perfectly mixed. The concentration of any reactant does not vary either in space or time. Conversion rate is the lowest among the flow reactors. But, in a Plug-fIow Reactor (PFR), the reactants are continuously introduced and the products and unreacted reactants continuously removed. There is no mixing of the contents in the axial direction through the reactor. The concentration of any reactant changes in both space and time. Conversion rate is the highest among all the flow reactors.

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III. MODELLING ANIMAL GUT AS REACTOR

Chemical reactor models of the digestive system and its components have provided an important framework to quantitatively study physiological processes involved in food processing. Penry and Jumars [12] have presented elaborate reaction kinetics, mass balance and rate equations by assuming animal guts to be either one of three reactor types; batch reactor, PFR or continuous-flow stirred-tank reactor (CFSTR). Accordingly, the gut should function as a plug-flow reactor when dealing solely with regular digestion kinetics catalyzed by enzymes secreted by the animal. Microorganism mediated fermentation or decomposition in animals, coupled with reasonably short throughput time indicate a CSTR/PFR series in gut behaviour. Later researches [13] indicated that tubular guts are morphological expressions of plug flow, and are common among deposit feeders, allowing relatively rapid ingestion rates and short throughput times. Reactor design models can be successfully employed to model the guts of variety of animals. According to Horn & Messer [13], Stomach of an animal can be predicted as a batch or CSTR, the intestine as a PFR and hindgut caecum as a CSTR. Tubular guts predominate among multicellular animals and the flow of digesta through tubular guts can be described quite reasonable by the PFR model. Gut reactor models are more successful than compartmental models in describing the flow patterns of digesta. In modelling an animal gut as reactor, Gut architecture, gut capacity, intake level, diet composition, digesta passage rate and digestion rate (Operating variables) are all the factors affecting digestibility of materials [14]. Throughput time is the ratio of gut volume to volumetric throughput rate, conversion increases as gut volume increases relative to throughput time or as throughput time decreases relative to gut volume. Throughput rates are smaller in foregut fermenters (CSTR-PFR) than in hindgut fermenters (PFR-CSTR) of similar size. Large body size, longest throughput times and highest conversion efficiencies, foregut fermentation may be accomplished efficiently by PFR.

Digestion begins when the food is consumed. Carbohydrates, fats, and protein are broken down in parts of the gut into simpler compounds like sugars, alcohols and fatty acids, and amino acids. These can then be absorbed (or assimilated) across the gut wall into the animal's circulatory system where they are distributed to the organism's energy budget to carry out basic organism activities: maintenance and respiration, reproduction, growth or production, and storage. In most of the organisms, Carbon (C), Phosphorous (P) and Nitrogen (N) are the vital nutrients which affect growth, metabolism and the maintenance of homeostasis. These nutrients represents as an index of food quality. An elemental approach can also complement an experimental program where basic chemical elements (C, N, and P) of the food, the organism, and the egesta can be measured. J.D. Logan *et al* [15] showed how modulation works in three nutrient (C, N and P) systems and developed a model that controls consumer homeostasis through dynamic differential assimilation. A static, two nutrient (C and P) case was studied by Sterner R.W [16] and Frost *et al* [17]. Woods H.A and Kingsolver J.G [18] developed a chemical reactor model of the caterpillar midgut, and used the model as a framework for generating hypotheses about the relationship between feeding responses to variable protein and the physical and biochemical events in the midgut and body. Application of such ideas to digestion processes in simple organism provides a quantitative framework for addressing many complex questions about digestion processes in both vertebrates and invertebrates up and down the complexity scale [19].

IV. EARTHWORM'S GUT

The activity of the earthworm gut is like miniature composting tube that mixes, conditions and inoculates the residues. Moisture, pH, enzymes and microbial populations in the gut are favorably maintained for a synergistic relationship, and then a terrific by-product.

When the organic materials pass through the earthworm gut, the resulting vermicast is rich in microbial activity, plant growth regulators and pest repellents [20]. Earthworm's gut is an effective tubular reactor, which maintains a suitable temperature through novel temperature regulatory mechanisms, thus accelerating the rates of the bioprocesses and preventing enzyme inactivation caused by high temperatures [21].
According to Edwards & Bohlen [22], the earthworm gut is a straight tube which extends from mouth to anus. The food enters through the mouth and gets sucked in by pharynx. Food particle moves to crop which acts as temporary storage and is mixed together. After leaving crop, partially mixed food particles enter gizzard where the actual digestive process begins. The powerful muscles of the gizzard churn and mix the mass of food and dirt. The mixture is reduced to a thick paste once the churning and mixture is complete. Glands in the walls of the gizzard add enzymes, which aid in the chemical breakdown of the organic material. The mixture is then sent to the intestine. The intestine has friendly bacteria that act on the food mixture. While the mixture is being eaten it releases various vitamins, minerals, carbohydrates, and proteins from the organic matter; this supply everything the worm needs in order to absorb it into its body. Most of the worm's body length is intestine. It is lined with thousands of finger-like projections that are filled with small blood vessels. The blood vessels help to absorb the liquefied food. Finally at the end of the intestine, the soil particles and undigested organic matter pass out of the worm's body through the anus. The waste is deposited in a form called a worm cast. The worm cast is mostly just ground up soil. By the time it comes out of the worm it has become enriched, acid neutralized, and revitalized.

V. EARTHWORM'S GUT ENZYMES

According to Lakshmi & Indira [21], Earthworms are physically aerators, crushers and mixers; chemically degraders and biologically stimulators in decomposer system. These worms have in-house supply of enzymes such as amylase, cellulose, nitrate reductase, acid and alkaline phospatases. These enzymes degrade the complex biomolecules into simple compounds and responsible for the decomposition and humification of organic matter. These enzymes are active at a very narrow pH range and efficiently maintain the highly non-linear pH parameters. Amylase, cellulose, acid phosphatase, alkaline phosphatase and nitrate reductase were secreted in the gut of the earthworms due to the increased presence of microorganisms in it.

Cellulase activity is maximal in the posterior region of the gut of the worms supports the view that microorganisms present in the fore and mid gut might be helping in the partial digestion and processing of the complex plant remains which contains cellulose, xylan, manna, pectin etc [23].Earthworm produces an enormous amount of intestinal mucus composed of gluco-proteins and small glucosidic and proteic molecules [20]. Naturally occurring plant-remains ingested by worms are very complex, consisting of starch, cellulose, xylan, galactine and protein substances. These complex organic molecules are digested through a mutualistic earthworm microflora-digestion system. Amylase, cellulose, xylanase, endoglucanase, cellobiase, acid phosphatase, alkaline phosphatase and nitrate reductase produced by jointly earthworms and gut microflora are supposed to play a central role in the process of digestion and humification of soil organic matter [21]. The intestine of earthworm contains microorganisms and gut enzymes. Similar to the occurrence of greater number of microbes in the gut of earthworms, the cast also contains more microoraganisms [24].

VI. EARTHWORM'S GUT MICROFLORA

Enzymes are produced jointly by worms and gut microflora plays a central role in the process of digestion and humification of soil organic matter. The gut of earthworm is continuously exposed to numerous microorganisms ingested from the external environment [25]. The biochemical decomposition of organic matter is primarily accomplished by the microbes; however, earthworms are crucial drivers of the process by fragmenting and conditioning the substrate, and by increasing the surface area of organic matter available for microbial attack after comminution [26]. Essentially epigeic earthworms directly affect the decomposition of organic matter through gut-associated processes, via the effects of ingestion, digestion and casting [27], [28].

According to Sruthy *et al* [24], the gut of the earthworm constitutes a unique microenvironment in soils. Microoraganisms constitute an important diet (Microbvorous). Qualitative and quantitative surveys of microbial flora of various earthworms are still warranted. It was observed that there are variations in the population of microorganisms in the foregut, midgut and hindgut of earthworm. The variation in the microbial populations in the earthworm gut may be because of their nutritional needs and digesting ability of the earthworms. The selective digestion of microbes in the gut influences the type of nutrients that are available for subsequent assimilation by both the earthworm and members of the gut microflora. The survival of microbes in the earthworn gut depends on their capacity to resist to digestive enzymes of microbial or earthworm origins, intestinal mucus, calcium carbonate or to bacteriostatic and microbial substances. The predominant microorganisms found in the foregut, midgut and hindgut were bacteria, actinomycetes and fungi. The bacteria in the foregut helps to digest the food particles, actinomycetes in the midgut helps to destroy the pathogens by antagonistic activity, and the fungi help to bind the waste particles as castings in the hindgut. The microbes entering the worm guts consume mucus, which mainly increase their activity, which in turn enables them to contribute enzymes to the digestive processes of the earthworms. These enzymes come with the ejected materials of earthworms. The increase in the counts of bacteria and yeasts along the gut of earthworm is due to increase in availability of nutrients in the gut [20]. An increasing appreciation of the synergistic interactions between earthworm and microorganisms is observed [29] . Despite of the studies so far, the real existence of symbionts in the earthworm gut is still controversial [30]. However some other studies show some evidence of earthworm gut symbionts. It was found that some microorganisms in the earthworm intestine that are absent in the surrounding soil and important changes in the fatty acid concentration and composition in the gut of earthworm, *L. terrestris*.

VII. EARTHWORM'S GUT AS REACTOR

In treating the worm (tubular gut) as a reactor, various aspects require consideration, such as the rate of reactant passage via the worm gut, which invariably determines the type of reactor kinetics involved. Enzymatic kinetics need to be considered as well; this would enable the chance of determining the effectiveness of employing nitrogen content as a viable substitute for protein content, while relationship constants can be used to ascertain cast stability. Digestion in earthworm guts occur via metabolic pathways that involve enzymatic conversions of complex carbohydrates and proteins to intermediate products such as peptides, free amino acids and monosaccharide sugars [31]. Michaelis-Menten kinetics deal with the catalytic action of enzymes on substrates, with the assumptions that there is the formation of an enzyme-substrate complex, the complex attains rapid equilibrium with free enzyme and that the breakdown of the complex into products is the rate determining step [32]. The general scheme for the enzyme catalyzed reaction under steady state conditions results in the dual nature of the kinetic equation, i.e., the reaction rate exhibits both zeroth and first order dependence towards S. A plot of the initial reaction velocity against the concentration of S gives the characteristic rectangular hyperbola, with the maximum velocity asymptotically ascertained from the plateau range of the curve; the Lineweaver-Burk method plots reciprocals of the said variables [33]. For purposes of accuracy, linear transformations of the equation require to be tested as the velocity is subject to experimental error, although the substrate concentration can be controlled by the investigator [34].

CONCLUSION

Several researchers model animal guts as reactors, although not many discuss earthworms specifically [12], [13], [35]. To date, most studies dealing with the role of the earthworm species in waste management have focussed on the changes before and after vermicomposting [28], [36], [37], rather than those occur throughout the process. There is as yet research that correlates the earthworm gut to concepts of a Plug Flow Reactor (PFR). That is to say, we're not sure if fluids are completely mixed in any given cross section throughout the gut length, while contiguous cross sections or unit volumes do not exchange mass with each other in a worm, as with in PFR's. Research on various worm feed sources include biosolids [38], fruit and vegetable waste [39], newspaper and cafeteria waste [40], as well as dung [41] have not cited the effects of feed types on worm digestion kinetics or vermicast nutrient compositions. There is lack of research on the effects of various feed source mixes on the vermicast nutrient compositions as well.

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Table 1: Recent works considering animal guts as reactors

Year	**Researchers**	**Animals**
19867	Penry & Jumars	Deposit feeders. (e.g., Polychaete annelids). Mammalian foregut fermenters. (e.g., Kangaroos, cows, sheep). Hindgut fermenters. (e.g., Horses. rabbits).
1988	Carlson & Alice	Deposit feeders. (e.g., Vampire bat, Sea anemone, Starfish) Foregut fermenters. (e.g., Hippopotamus) Hindgut fermenters. (e.g., Koala bear, Manatee)
1989	Hume I.D	Mammalian Herbivores.
1990	Martinez del Rio et al	Nectar and fruit eating birds.
1992	Horn & Messer	Marine herbivorous fishes.
1993	Yuelong yang	Insect herbivore, Grasshopper.

1996	Simpson & Raubenheimer	Locust, Caterpillar.
1999	Woods H.A & J.G. Kingsolver	Caterpillars
2002	Hume I.D	Mammalian carnivores. (e.g., Dogs, Cats) Mammalian omnivore. (e.g., Rats) Mammalian foregut fermenters. (e.g., Sheep, Kangaroo) Hindgut fermenters. (e.g., Pony, Rabbit)
2005	Wolesensky & David Logan	Herbivore consumers, Grasshoppers.
2010	Rodney Van Bentum *et al*	Passage of food through animal stomach.

Source: [11], [12], [13], [19],[42], [43], [44], [45], [46], [47].

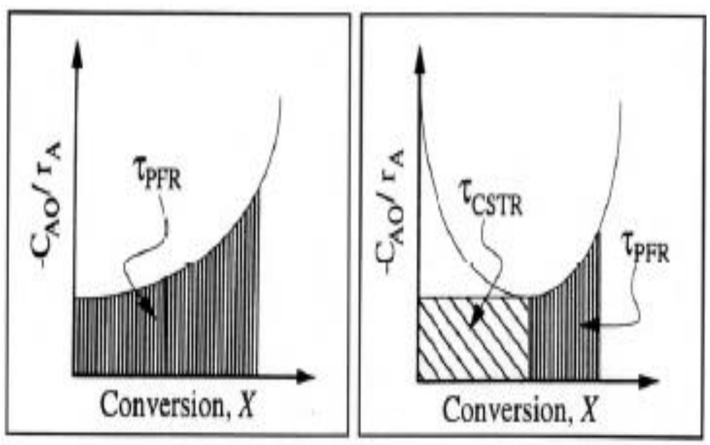

Fig 1: Graphical design equation for PFR and CSTR Source: [42]

REFERENCES

[1] Domínguez, J., (2004) State of the art and new perspectives on vermicomposting research. In: Edwards, C.A. (ed.): Earthworm Ecology, pp. 401–424.
[2] Suthar S. (2010) Pilot-scale vermireactors for sewage sludge stabilization and metal remediation process: Comparison with small-scale vermireactors. Ecological Engineering 36:703-712.
[3] Ansari (2011), Worm powered environmental biotechnology in organic waste management. *Int. J. Soil Sci..* 25-30.
[4] Turgay O.C., Kizilkaya R., Karaca A., Cetin S.C. (2011) Detoxification of heavy metals using earthworms. Soil Biology 30:407-421.
[5] Lavelle P. (1988) Earthworm activities and the soil system. Biolo. Fertil. Soils 6:237-251.
[6] Nasiru, A., Jessy, R.S., Ibrahim, M.H. (2012) Effect of Nutrients Digestibility on Vermicomposting of Ruminant Manure: A Review. UMT 11th International Annual Symposium on Sustainability Science and Management. 215-221.
[7] Resdi R., Jessy, R.S., Ibrahim, M.H. (2012) Use of Vermicast Derived from Cow Dung and Goat Manure as Fish Pond Fertilizer-Effect on Water Quality. UMT 11th International Annual Symposium on Sustainability Science and Management. 32-36.
[8] Majeed M.Z., Miambi E., Barois i., Blanchart E., A Brauman (2013) Emission of nitrous oxide from casts of tropical earthworms belonging to different ecological categories. Pedobiologia 56:49-58.
[9] Li K., Li P., Li H. (2010) Earthworms helping economy, improving ecology and protecting health. Int. Journal of Global Environmental Issues 10:3-4.
[10] Sinha R.K. (2009) Earthworms: the miracle of nature (Charles Darwin's 'unheralded soldiers of mankind and farmer's friends'). Environmentalist 29:339-340.
[11] Yuelong Yang, "The insect herbivore gut as a series of chemical reactors: Mathematical modeling and empirical evaluation" (January 1, 1993). *ETD collection for University of Nebraska-Lincoln.* PaperAAI9331436b.
[12] Penry D.L., Jumars P.A. (1987) Modelling animal guts as chemical reactors. The American Naturalist 129(1):69-96.
[13] Horn M.H. and Messer K.S. Fish Guts as chemical reactors: a model of the alimentary canals of marine herbivorous fishes. Marine Biology 113:527-535.
[14] Parra, R., (1978), Comparison of foregut and hindgut fermentation in herbivores, Pages 205-229 in G. G. Montgomery, ed, The ecology of arboreal folivores, Smithsonian Institution Press, Washington, D.C.
[15] Logan *et al* (2004), Chemical reactor models of optimal digestion efficiency with constant foraging costs, *Ecological Modelling* 168, 25-38.
[16] Sterner, R. W. (1997) Modelling interactions of food quality and quantity in homeostatic consumers, Freshwater Biology 38, 473–481).
[17] Frost, P. C. & Elser, J. J. (2002) Growth responses of littoral mayflies to the phosphorus content of their food, Ecology Letters 5, 232–240.
[18] Woods, H.A., J.G.Kingsolver (1999), Feeding Rate and the Structure of Protein Digestion and Absorption in Lepidopteran Midguts, Archives of Insect Biochemistry and Physiology 42:74–87.

[19] William Wolesensky *et al* (2005), A model of digestion modulation in grasshoppers, Ecological Modelling 188 (2005) 358–373.
[20] Bill Becker., (1991) The Benefits of Earthworms, Natural food and farming, July/August, p12.
[21] Indira & Lakshmi (2007), Comparative studies on the digestive enzymes in the gut of earthworms, *Eudrilus eugeniae* and *Eisenia fetida,* Indian Journal of Biotechnology Vol 6, pp 567-569.
[22] Edwards & Bohlen (1996), Biology and Ecology of Earthworms, Chapman & Hall, London, Page 73-74.
[23] Mishra and M.C. Dash (1979), Digestive enzymes of some earthworm, Experien – tic., Vol. 36, No. 10, 1156 – 57, 1980.
[24] Sruthy *et al* (2013), Screening of earthworm *Eudrilus eugeniae* gut as a transient microbial habitat, Advances in zoology and botany 1(3): 53-56.
[25] Jolly *et al* (1997), Scanning Electron Microscopy of the Gut Microflora of Two Earthworms: *Lumbricus terrestris* and *Octolasion cyaneum,* Microb Ecol (1993) 26:235-245.
[26] Domínguez, J., Aira, M., and Gómez-Brandón, M., (2010) Vermicomposting: earthworms enhance the work of microbes. In: Insam H, Franke-Whittle H and Goberna M (eds) *Microbes at Work: from Wastes to Resources*. Berlin: Springer, pp. 93–114.
[27] Aira, M., and Domínguez, J., (2009) Microbial and nutrient stabilization of two animal manures after the transit through the gut of the earthworm *Eisenia*, Vol 161, Pages 1234–1238.
[28] Gómez-Brandón M, Lores M and Domínguez J (2012) Species-specific effects of epigeic earthworms on microbial community structure during first stages of decomposition of organic matter. *Plos One* 7: 1–8.
[29] Sumathi & Arockiam (2012), Impact of organic rich diet on gut enzymes, microbes and biomass of earthworm, *Eudrilus eugienea*, Journal of Environmental Biology, ISSN: 0254-8704.
[30] Parthasarathi et al, Diversity of microflora in the gut and casts of tropical composting earthworms reared on different substrates. *J. Environ. Biol.*, 28, 87-97 (2007).
[31] Karasov W.H., Diamond J.M. (1988) Interplay between physiology and ecology in digestion. BioScience 38(9):602-611.
[32] Atkins, P., de Paula, J. (2006) Physical Chemistry for the Life Scienecs. New York, NY: W.H. Freeman and Company. Page 363-371.
[33] Dawson, E.A., Samanta, S., Caramori, S.S., Savage, K., (2012) The Dual Arrhenius and Michaelis–Menten kinetics model for decomposition of soil organic matter at hourly to seasonal time scales. Global Change Biology 18(1):371-384.
[34] Dowd J.E., Riggs D.S. (1965) A comparison of estimates of Michaelis-Menten Kinetic constants from various linear transformations. The Journal of Biological Chemistry 240(2):863-869.
[35] Caton, J., and Hume, I.D., (2000) Chemical reactors of the mammalian gastro-intestinal tract. Zeitschrift fur Saugetierkunde 65(1):33-50.
[36] Lazcano C, Gómez-Brandón M and Domínguez J (2008) Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. *Chemosphere* 72: 1013–1019.
[37] Vivas A, Moreno B, García-Rodríguez S and Benítez E (2009) Assessing the impact of composting and vermicomposting on bacterial community size and structure, and microbial functional diversity of an olive-mill waste. *Bioresource Technology* 100: 1319–1326.
[38] Ndegwa P.M., Thompson S.A., Das K.C. (2000) Effects of stocking density and feeding rate on vermicomposting of biosolids. Bioresource Technology 71:5-12.
[39] Pattnaik S. and Reddy V.M. (2010) Nutrient status of vermicompost of urban green waste processed by three earthworm species-*Eisenia fetida, Eudrilus eugeniae*, and *Perionyx excavatus*. Applied and Environmental Soil Science 2010:1-13.
[40] Hasnah M.J. and Hansuri M.H. (2008) Waste conversion to vermicast by eisenia foetida given four types of organic substrates in the natural Malaysian environmental conditions. Journal of Bioscience 19(2):63-72.
[41] Garg V.K., Yadav Y.K. and Sheoran A. (2006) Livestock excreta management through vermicomposting using epigeic earthworm Eisenia foetida 26:269-276
[42] Eric D. Carlson., Alice P. Gast (1988), Animal gut as ideal reactors, An open ended project for a course in kinetics and reactor design, *ChE division of ASEE, Winter* pp 24-29.
[43] Hume, I. D., (1989) Optimal digestive strategies in mammalian herbivores. Physiological Zoology 62:1145–1163.
[44] Martı´nez del Rio, C., and W. H. Karasov. 1990. Digestion strategies in nectar- and fruit-eating birds and the sugar composition of plant rewards. American Naturalist 136: 618–637.
[45] Simpson S.J. & D. Raubenheimer (1996), Feeding behaviour, sensory physiology and nutrient feedback: a unifying model, *Entomologia Experimentalis et Applicata* 80, 55-64.
[46] Hume, I. D., (2002), Digestive strategies of mammals, *Acta Zoologica Sinica* 48(1), 1-19.
[47] Rodney Van Bentum *et al* (2010), Modelling the passage of food through an animal stomach: A chemical reactor engineering approach, Chemical Engineering Journal 166 (2011) 315–323.

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