Mechanisms, Performance, and Challenges of Anaerobic Digestion with Conductive Materials

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Abstract

Utilizing organic waste as a resource is made sustainable and efficient *via* anaerobic digestion. Direct Interspecies Electron Transfer (DIET), which facilitates the syntrophic conversion of different organics to methane, has recently gained attention through the use of conductive materials during anaerobic digestion. The most recent research on DIET processes with various mediating pathways is thoroughly summarised in this study. The impact of diet on the efficiency of anaerobic digestion as well as the underlying mechanisms affecting the lag phase, methane generation, and system stability are all being extensively investigated. Current issues are also thoroughly examined, including ambiguous biological mechanisms, the effects of non-diet mechanisms, the limitations of organic materials syntrophically oxidised by means of diet, and issues with the practical application of diet mediated by conductive materials. Finally, prospective research directions for the use of diet in practice are presented.

Keywords: Organic waste • Direct interspecies electron transfer • Anaerobic digestion • Conductive materials • Organic materials

Introduction

Anaerobic digestion's ability to produce methane can help the world achieve its present sustainable development goals of combating climate change, recycling trash, and producing clean energy. The process of anaerobic digestion typically involves four kinds of microorganisms (fermentative bacteria, acidogens, acetogenes, and methanogens) with distinct metabolic roles [1]. These microorganisms differ in their physiology, nutrition metabolism, growth dynamics, and sensitivity to the environment. As a result, there are many complicated interactions between bacteria during the entire anaerobic digesting process. Bacteria are more flexible to changes in pH and have a shorter generation time and faster growth rate than methanogens. The effectiveness of anaerobic digestion is typically hampered by the imbalance between methanogens and bacteria. Therefore, the effective syntrophic connections between bacteria and methanogens are crucial to the process of anaerobic digestion [2].

Literature review

Interspecies Formate Transfer (IFT) and Interspecies Hydrogen Transfer (IHT) have long been thought to be the two main interspecies electron transfer modalities in syntrophic oxidation of organic materials.

However, the thermodynamically unfavourable reaction of H_2 generation in syntrophic oxidation with energy consumption [3]. Direct Interspecies Electron Transfer (DIET), which transfers electrons directly from electron donors to electron acceptors with fewer biological enzymatic steps, has recently been demonstrated to represent a new syntrophic association mechanism. Since diet does not require H_2 as an electron carrier, it can substitute IHT in anaerobic digestion systems and get over the thermodynamic restriction at high hydrogen partial pressure. The electron transfer rate based on DIET was 8.57 times greater than that based on IHT, according to a mathematical model. As a result, DIET's electron transfer capacity is more effective than IHT's. The ability of Geobacter species to form DIET based syntrophic relationships with methanogens has been demonstrated. This is done by using conductive pili (e-pili) and c-type cytochromes (OmcS), in which methanogens take electrons and convert CO_2 to methane. Studies have demonstrated that by introducing conductive materials as Granular Activated Carbon (GAC), bio char, carbon cloth, carbon nanotube, graphene, and magnetite, other bacteria that cannot manufacture e-pili or OmcS may also form diet based syntrophic relationships [4]. It is commonly accepted that the role of e-pili or OmcS is replaced by non-biological conductive materials acting as an electrical conduit.

The discovery of diet offers a fresh method for enhancing the efficiency of anaerobic digestion. Over the years, anaerobic digestion systems using a variety of substrates have been successfully used to implement diet mediated by conductive materials. Recently, a number of related reviews that further on the significance and benefits of diet mediated by conductive materials have been published. There are, however, few articles that thoroughly summarise the workings of diet and its implications on anaerobic digestion performance when diet is mediated by conductive materials. Furthermore, there are a few important questions that require an answer [5]. Other stimulatory mechanisms of conductive materials, such as microbial immobilisation, buffering effect, and adsorption effect, which are connected to the surface physico-chemical properties of conductive materials, such as large surface area, rich redox groups, and surface pH, also influence the performances of anaerobic digestion in addition to diet. Because it might be challenging to estimate the contribution of non-diet function to methane production, these knowledge components should be taken into account. While certain substrates and microorganisms are just hypothesised to be involved in diet based on anaerobic digestion performance improvement and microbial features, only a small number of substrates and microorganisms have been proven to be involved in diet. Furthermore, the practical implementation of diet is constrained by the detrimental effects of conductive materials on downstream processing, the environment, and anaerobic digestion performance. For a clearer understanding of the practical application, a review of the literature on the mechanisms, performances, and difficulties of improving diet with the use of conductive materials in anaerobic digestion is essential.

Discussion

The advantages and negative impacts of diet mediated by conductive materials in anaerobic digestion systems are thoroughly explored in this review, which also provides a thorough summary of the fundamental mechanisms of diet. Additionally, this review emphasises current issues and critically examines the murky biological mechanisms of diet, the effects of non-diet mechanisms, the limitations of organic materials syntrophically oxidised by means of diet, and difficulties in the practical application of diet mediated by conductive materials. Finally, it is anticipated that the future research prospects for diet outlined here will serve as a theoretical foundation and point of reference for actual application.

Conclusion

In terms of electron transfer effectiveness and energy conservation, the diet has been shown to be more effective than IHT. As a result, the development of diet with the addition of conductive materials can considerably improve the performances of anaerobic digestion, and has received growing attention in recent years. The mechanisms of diet and the promoting effect of diet on the anaerobic digestion system are outlined in this review. The limitations of organic materials syntrophically oxidised by way of diet, issues in practical application of diet mediated by conductive materials, and uncertain biological mechanism of diet are just a few of the current obstacles presented in this review based on our understanding. Therefore, further thorough exploration studies are required to close the knowledge gaps in the pertinent area.

It is challenging to follow electron transfer routes throughout the diet process and identify all proteins and structures involved due to biological constraints and technical limitations. In order to offer a theoretical foundation for the use of diet mediated by conductive materials in anaerobic digestion, more study is therefore required to examine the biological mechanisms of diet [6]. The current studies only hypothesised that diet occurred in anaerobic digestion based on the following phenomena:

- The microbial aggregates displayed metal like electrical conductivity.
- Geobacter, methanosaeta, and methanosarcina were dominant in the microbial community structure; and
- The anaerobic digestion system could overcome the restriction of hydrogen partial pressure. However, the knowledge regarding diet enhancement by conductive materials is limited.

However, these studies did not provide direct evidence for these conclusions. As a result, more research is needed to understand how microbes and conductive materials interact. Anaerobic digestion uses a complicated metabolic network to break down complex organic materials. Future studies are therefore required to identify more bacteria capable of diet, which opens the door to the possibility of complex organic materials participating in the diet metabolic pathway. The application of diet in anaerobic digestion may also benefit from interdisciplinary research because it requires the fusion of several disciplines, including microbiology, biochemistry, material science, and others to establish diet mediated by conductive materials.

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