In search of a thermodynamic description of biomass yields for chemotrophic growth of microorganisms

J.J. Heijnen

Delft University of Technology, Dept. of Biochemical Engineering, Julianalaan 67, 2628 BC Delft, The Netherlands

Abstract

Chemical and thermodynamic approaches to estimate biomass yields have been evaluated with respect to their general applicability, the absence of intrinsic problems and their relation to the 2nd law of thermodynamics. None of the methods appears to satisfy these 3 criteria. However a method based on Gibbs energy dissipation is proposed, which satisfies these 3 requirements, and provides very good results for biomass yield estimations.

Correlations for the prediction of biomass yields are valuable and many proposals based on a number of chemical parameters have been published (Y_{ATP}, Y_{Ave}, η_o, Y_c). Published energetic parameters are black box enthalpy efficiency η_H, black box Gibbs energy efficiency η^{BB} from Roels (Ref 1), the Gibbs energy conservation efficiency from Battley (Ref 2) and the Gibbs energy convertor efficiency η^{EC} (Ref 1,3). This work (Ref 4,5) critically examines the properties of the proposed parameters with respect to the general applicability to chemotrophic growth systems, a clear relation to the 2nd law of thermodynamics, the absence of intrinsic problems and a requirement of only black box information. It appears that none of the proposed parameters satisfies all these requirements. Their range of application is too limited (Y_c, η_o), most have no relation to the 2nd law of thermodynamics (Y_{ATP}, Y_c, η_o, Y_{Ave}, η_H) and all the proposed Gibbs energy efficiencies from Battley, Roels and Westerhoff are based on implicit assumptions which are highly unrealistic from a general biochemical point of view (Ref 4,5). Evolutionary implications of the calculated η^{EC} values (Ref 3) are therefore invalid.

However it is shown that the Gibbs energy dissipation per amount of produced biomass (kJ/C-mol) is a parameter which satisfies the requirements without having intrinsic problems. A simple correlation is found which provides the Gibbs energy dissipation/C-mol biomass as a function of the nature of the C-source (expressed as the carbon chain length and the degree of reduction). This dissipation appears to be nearly independent of the nature of the electron acceptor (e.g. O_2, NO_3^-, fermentation). Hence a single correlation can describe a very wide range of microbial growth systems. In this respect Gibbs energy dissipation is much more useful than heat production/C-mol biomass, which is strongly dependent on the electron acceptor used. Evidence is presented that even a net heat-uptake can occur in certain growth systems.

The correlation of Gibbs energy dissipation thus obtained shows that dissipation/C-mol biomass increases for C-sources with smaller chain length ($C_6 \rightarrow C_1$) and increases for both higher and lower degrees of reduction than 4. It appears that the dissipation per C-mol biomass can be regarded as a simple thermodynamic measure of the amount of biochemical "work" which is required to convert the carbon source into biomass by the proper irreversible carbon-carbon coupling and oxidation/reduction reactions.

This is supported by the good correlation between the theoretical ATP-requirement for biomass formation on different C-sources and the dissipation values (kJ/C-mol biomass) found. The established correlation for the Gibbs energy dissipation allows the prediction of the chemotrophic biomass yield on substrate with an error of 13% in the yield range 0.01-0.80 C-mol biomass/C-mol substrate for aerobic/anaerobic /denitrifying growth systems. Recently a black box model has been published (Ref 6) to calculate Y_{DX} directly from Gibbs energy dissipation. A very simple mathematical equation is found based on degrees of reduction and the Gibbs energy level of the electrons in biomass, electron donor and acceptor. Also simple equations are found to calculate maximal Y_{DX} values from the 2nd law.

REFERENCES

1. J.A. Roels, Energetics and Kinetics in Biotechnology, Elsevier, Amsterdam (1983).
2. E.H. Battley, Energetics of Microbial Growth, Wiley, New York (1987).
3. H.V. Westerhoff and K. van Dam, Thermodynamics and Control of Biological Free Energy Transduction, Elsevier, Amsterdam (1987).
4. J.J. Heijnen, Antonie van Leeuwenhoek 60, 235-256 (1991).
5. J.J. Heijnen, and J.P. van Dijken, Biotechnol. Bioeng. 39, 838-858 (1992).
6. J.J. Heijnen, M.C.M. van Loosdrecht and L. Tijhuis, Biotechnol. Bioeng. 40, 1139-1154 (1992).