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PHOTOOXIDATION OF MONOSACCHARIDES WITH METAL CATALYSIS. OXIDATION WITH ATMOSPHERIC OXYGEN BY COUPLING WITH THE OXIDATION-REDUCTION CYCLE OF METAL IONS

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D-Fructose was oxidatively degraded to D-erythrose by atmospheric oxygen with irradiation of a Pyrex-filtered light in the presence of catalytic amount of $FeCl_3$ at near neutral pH range. The reaction proceeded by coupling with the oxidation-reduction cycle of iron ion. D-Glucose-$FeCl_3$ and D-fructose-$MnCl_2$ systems were also found to be susceptible to the catalytic photooxidation.

Trace amount of metal ion often plays essential role in many biological systems. Because of the physiological and clinical importance, interaction or complex formation of metal ion with carbohydrates has been the subject of intense studies.[1] However, only a little has yet been known as to the photochemical properties of metal-carbohydrate systems.[2,3] We previously reported that D-fructose was oxidatively degraded to D-erythrose in an acidic $FeCl_3$ solution (pH<2) by irradiation of a Pyrex-filtered light according to the equation 1.[4]

$$\text{D-fructose} + 2\text{Fe(III)} \xrightarrow{h\nu} \text{D-erythrose} + 2\text{Fe(II)} + 2\text{H}^+ \quad (1)$$

An attempt to study this reaction at physiological pH range usually resulted in the precipitation of Fe(III) as a hydroxide. However, the presence of large excess of D-fructose allows Fe(III) in a solution by formation of a Fe(III)-D-fructose complex, and an aqueous $FeCl_3$ solution remains clear even at weakly acidic to weakly basic pH range.[3,5] We now report the results of the irradiation of a Pyrex-filtered light to a D-fructose-$FeCl_3$ solution of this pH range, which demonstrate that D-fructose is oxidatively degraded to D-erythrose with atmospheric oxygen by the catalytic action of iron ion.

An aqueous $FeCl_3$ (2×10^{-3} mol·dm^{-3})-D-fructose ($1 - 4 \times 10^{-1}$ mol·dm^{-3}) solution whose pH was adjusted to 9.6 by addition of concd NaOH showed no precipitation. The solution (70 ml) was irradiated internally by a 100 W high-pressure mercury lamp through a Pyrex jacket at 20°C with air bubbling. After an hour of irradiation, the pH of the solution, which decreased to 6.2-6.5, was readjusted to 9 by addition of a small amount of concd NaOH solution. The pH readjustment was done every one hour of irradiation to keep the pH of the solution within the

Table 1. Photooxidation of Monosaccharides in the Presence of Metal Salt (1.4×10^{-4} mol) at 20 °C[a)]

#	Metal salt	Irradiation time/h	Substrate/10^{-3} mol		Product/10^{-3} mol[b)]		Turn-over[c)]
				Initial	Oxidized	D-Arabinose	D-Erythrose	
1	$FeCl_3$	9	D-fructose	7.0	2.0	-	1.2 (60%)	29
2	$FeCl_3$	12	D-fructose	28.0	9.1	-	6.7 (74%)	130
3	$FeCl_2$	12	D-fructose	28.0	8.5	-	6.2 (73%)	121
4	$FeCl_3$	6	D-glucose	28.0	4.9	1.0 (20%)	trace	70
5	$MnCl_2$	8	D-fructose	28.0	8.4	-	4.8 (57%)	120
6	$MnCl_2$	24	D-fructose	28.0	15.4	-	8.7 (56%)	220

a) D-Fructose, D-glucose, and D-arabinose were analyzed by HPLC[4)], and D-erythrose by GLC after acetylation according to the method of Wachowiak and Connors.[6)]
b) Conversions based on the substrate oxidized were given in parentheses(mol%).
c) Turn-over of metal by assuming that 2 mol of metal(III) oxidizes 1 mol of sugar.

range between 6 and 9.6 throughout the reaction. After certain period of irradiation, brown colloidal precipitate was formed, and no further reaction seemed to proceed thereafter. Analyses of the irradiated solution were made by the procedure described previously.[4)] Table 1 shows that more than 50 times of D-fructose to the initial $FeCl_3$ in molar ratio was oxidized (#2). The main oxidation product was D-erythrose.[6)] No detectable decrease in D-fructose was observed without irradiation, or in the absence of any one of $FeCl_3$ or oxygen. Use of $FeCl_2$ instead of $FeCl_3$ showed practically no difference. The results suggest that D-fructose is photo-oxidized with atmospheric oxygen by a catalytic action of iron ion.

To elucidate the role of iron ion further, we carried out the reaction under nitrogen atmosphere. The initial brown solution became dark-green on irradiation. Absorption spectrum of the irradiated solution was similar to that of an $FeCl_2$-D-fructose solution prepared under anaerobic condition (Fig. 1(A)), and the formation of Fe(II) was further confirmed by the coloration reaction with 1,10-phenanthroline. Highest quantum yield for the reduction of Fe(III) was obserbed at 338 nm (Fig, 1(B)), indicating that the Fe(III)-D-fructose complex is the photoreactive species.[4)] Prolonged irradiation did not cause any detectable decrease in D-fructose. The results are substantially the same as those of the reactions in an acidic medium, indicating that D-fructose is oxidatively degraded to D-erythrose by Fe(III) with photo-irradiation according to the Eq. 1.

Introduction of oxygen to the pre-irradiated solution caused the change in color of the solution from dark-green to brown again with oxygen uptake (Fig. 1(A)), formation of Fe(III) being confirmed by the coloration reaction with potassium thiocyanate. This result is consistent with the fact that higher pH of a solution decreases the oxidation-reduction potential of Fe(III)/Fe(II), and, therefore, oxidation of Fe(II) by atmospheric oxygen takes place with appreciable rate.[7)] This cycle of the photoreduction and subsequent reoxidation of iron ion was confirmed to be repeatable. The amount of oxygen consumed during reoxidation of Fe(II) were 23 and 25 mol% of Fe(II) in the solution for the first and second cycles,

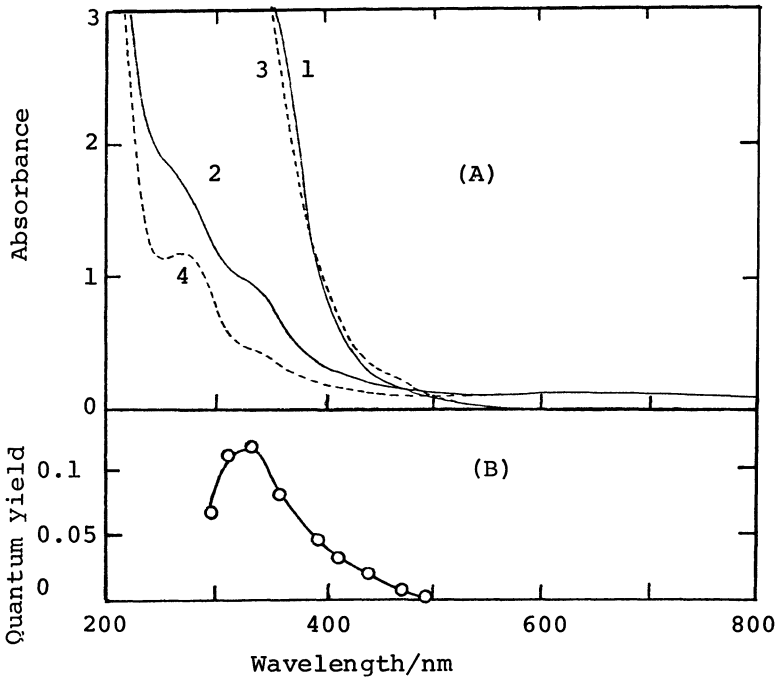

Fig. 1. Absorption and Action Spectra of an $FeCl_3$ (2×10^{-3} mol·dm^{-3})-D-Fructose (4×10^{-1} mol·dm^{-3}) Solution at pH 9.6 and 20 °C.
(A) Initial solution (1) was irradiated for 30 min under anaerobic conditions (2), and then the solution was aerated (3). Spectrum (4) represents an $FeCl_2$ (2×10^{-3} mol·dm^{-3})-D-fructose (4×10^{-1} mol·dm^{-3}) solution at pH 9.6 prepared under anaerobic conditions.
(B) Quantum yields of the reduction of Fe(III) at anaerobic conditions.

respectively.

Thus, the photooxidation of D-fructose by atmospheric oxygen is suggested to proceed by coupling with the oxidation-reduction cycle of iron ion. Though the details of the mechanism of this reaction are not yet clear, a possible mechanism is presented below (Eq. 2).

$$\begin{matrix}\text{D-fructose} \\ \text{D-erythrose}\end{matrix} \xrightarrow{h\nu} \begin{matrix}2\text{Fe(III)} \\ 2\text{Fe(II)} + 2\text{H}^+\end{matrix} \xrightarrow{} \begin{matrix}\text{H}_2\text{O} \\ \frac{1}{2}\text{O}_2\end{matrix} \qquad (2)$$

Turn-over of iron ion is estimated to be 130 times for #2 on the assumption that 2 mol of Fe(III) oxidizes 1 mol of D-fructose.

We are currently extending this study to other carbohydrate-metal ion systems. Table 1 includes the results of preliminary studies on the D-glucose-$FeCl_3$ and D-fructose-$MnCl_2$ systems, which are found to be susceptible to this type of photooxidation suggesting the wide applicability of this photoreaction to other carbohydrate-metal ion systems. Oxidation of D-glucose proceeded in the presence of $FeCl_3$ with air bubbling, though the brown colloidal precipitate was formed at much earlier stage of the reaction compared to that in the case of D-fructose. This might be due to the weaker complexing ability of D-glucose toward Fe(III) compared to that of D-fructose.[3] D-Arabinose and trace amount of D-erythrose were de-

tected as the oxidation products, being consistent with the former findings in the reaction in an acidic medium.[8] D-Fructose was also suggested to be oxidized by coupling with a Mn(III)-Mn(II) cycle to give D-erythrose. A $MnCl_2$-D-fructose solution at pH 9.6 under aerobic condition showed the characteristic Mn(III) band at 530 nm,[7] which disappered by irradiation of a Pyrex-filtered light under anaerobic condition and reappered by aeration of the solution. No precipitate was formed even after 110 times of D-fructose to $MnCl_2$ in molar ratio was oxidized.

These findings indicate that trace amount of transition metal can cause the oxidative degradation of carbohydrates at physiological condition by near UV to visible light. Since carbohydrates and metal ions are widely distributed in nature bearing variety of biological functions, these findings might imply physiological and clinical importance.

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References

1) S. J. Angyal, Pure Appl. Chem., 90, 131 (1973); J. Briggs, P. Finch, M. C. Matulewicz, and H. Weigel, Carbohydr. Res., 97, 181 (1981).
2) G. O. Phillips, Adv. Carbohydr. Chem., 18 , 9 (1963).
3) P. J. Charley, B. Sarkar, C. F. Stitt, and P. Saltman, Biochim. Biophys. Acta, 69, 313 (1963).
4) K. Araki, M. Sakuma, and S. Shiraishi, Chem. Lett., 1983, 665.
5) S. A. Barker, P. J. Somers, and J. Stevenson, Carbohydr. Res., 36, 331 (1974).
6) R. Wachowiak and K. A. Connors, Anal. Chem., 51, 27 (1979). Formation of D-erythrose was further confirmed by GC-mass spectrometry after acetylating the sample according to this method.
7) F. A. Cotton and G. Wilkinson, "Advanced Inorganic Chemistry," 3rd ed, John Wiley & Sons, New York (1956), Chap. 29.
8) K. Araki, M. Sakuma, and S. Shiraishi, Abstracts, 6th Japanese Carbohydrate Symposium, Sendai, Aug. 1983, p.34.

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