Characterisation of food fibres and their effect on starch digestion in an *in-vitro* system at physiological shear rates

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ABSTRACT

The fast pace of life promotes the excessive consumption of processed starchy food containing high levels of sugar, salt and oil; which can increase the prevalence of type II diabetes, colon and cardiovascular diseases. The addition of dietary fibres in the diet increases the viscosity of digesta, delays mixing in the gut, and promotes laxation. However, few studies attempt to quantify the possible physical and chemical effects of either soluble (food gums) and insoluble (largely cellulose) fibre in the diet. These effects may encompass the retention of water inside the fibre particles, between particles in the fibre mass and direct effects of the chemical nature of the fibre on the digestion process. In this study, the fractions of water held in the various partitions of insoluble particulate dietary fibres are quantified. The relationship between the volume fraction of soluble and insoluble dietary fibres in simulated digesta at physiological concentrations and the rheological properties of the suspension at physiological shear rates is determined. Furthermore, the impact of fibre and shear rates on the digestion of starch *in-vitro* at physiological shear rates was measured. This work provides the first quantitative assessment of the effects of the physical attributes of dietary fibre on the digestion of starch *in-vitro*, at physiological shear rates.

In this work, four insoluble fibre types were used to construct aqueous suspensions containing solid volume fractions similar to those of pig digesta from the small intestine, these suspensions also were shown to have similar rheological properties to those of pig digesta at physiological shear rates. In addition, a soluble fibre (Guar gum) was used to construct solutions with viscosities comparable to those of the

particulate suspensions. Gelatinised and partially gelatinised starch was added to these suspensions and its rate of digestion at 37°C under simulated small intestinal conditions was measured at shear rates covering the reported physiological range.

Important results from this work include:

- The proportion of water retained by a given volume of hydrated mass of large fibre particles (AllBran®) was double that of smaller particles (wheat fibre). For all of the solid particles used, the proportion of water sequestered by the intra-particulate voids was less than 4% of the volume of the particles, similar proportions were determined for indigestible particles recovered from the colon of pigs and from human faeces.

- Food fibre systems containing less than 20% by volume (solid volume fraction, $\phi = 0.20$) of insoluble dietary fibres showed Newtonian rheological properties and the viscosity of these suspensions could be predicted from ϕ by the Maron-Pierce model. Starch/fibre suspensions prepared with ϕ below 20% ($\phi = 0.68\text{-}0.98$) had a similar viscosity to that of starch/guar suspension comprising 10% (w/v) starch and 0.4% (w/v) guar.

  During *in-vitro* digestion, the viscosity of the starch/fibre suspensions decreased logarithmically over the first 20 minutes during which about 30% of the starch was hydrolysed, this was followed by a prolonged period of slow digestion as the slowly digested starch (SDS) and resistant starch (RS) were hydrolysed. The rate of starch digestion was independent of the type of insoluble fibre and was not affected by suspension viscosities used providing shear rates could be maintained within physiological levels. For guar, rates of digestion were slowed probably due to non-competitive inhibition of the amylase by the guar.

- When shear rates were below the physiological range (0.1 s^{-1}) or gelatinisation was incomplete, the rate of digestion became linear over the first 20 minutes of digestion suggesting that the rate of digestion was limited by transport processes at low shear in viscous suspensions.

- This study provides useful information regarding the limiting concentration of particles and hence viscosity of digesta in the gut if rates of digestion are to be maximised. Additionally, it is suggested that guar, even at low concentration may reduce glycemia by reducing rates of amylolysis.

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ADF	Acidic detergent fibre
ADL	Acidic detergent lignin
α	alpha
ANOVA	Analysis of variance
η_s	Apparent viscosity
R	Aspect ratio
AOAC	Association of Official Analytical Chemists
β	beta
BD	Breakdown
$CaCl_2$	Calcium chloride
c	Concentration of starch in a suspension
c*	critical concentration
°C	Degree celsius
DG	Degree of gelatinisation
ρ	density
DMC	Dry matter content
DNS	dinitrosalicylic acid
$Na_2EDTA\text{-}2H_20$	Disodium ethylenediaminetetraacetate dihydrate
dwb	dry weight basis
GLM	Generalised linear model
g	gram
g	Gravity force
h	hour
HCl	Hydrochloric acid
kg	kilogram
LiCl	Lithium chloride
L	litre
µl	Microlitre
µm	Micrometer
mg	Milligram

mL	Millilitre
mm	Millimeter
mmol/L	Millimolar/litre
min	minutes
M	Molar
MW	Molecular weight
nKat	nanokatal
NDF	Neutral detergent fibre
η_a	Newtonian suspending liquid
NSP	Non starch polysaccharides
Pa	Pascal
Pa.s	Pascal per second
PT	Pasting temperature
PV	Pasting viscosity
%	Percentage
s^{-1}	Per seconds
KCl	Potassium chloride
W_E	Proportion of extra particulate water
W_I	Proportion of intra-particulate water
RDS	Rapid digested starch
RVA	Rapid Visco Analyser
η_r	Relative viscosity
RS	Resistant starch
rpm	Revolutions per minute
SEM	Scanning electron microscope
SDS	Slow digested starch
$NaHCO_3$	Sodium bicarbonate
NaCl	Sodium chloride
$Na_2HPO_4 \cdot 2H_20$	Sodium phosphate dibasic dihydrate
$Na_2B_4O_7 \cdot 10H_20$	Sodium tetraborate decahydrate
ϕ	Solid volume fraction
ϕ/ϕ_{max}	Solid volume fraction to their maximum packing fraction
H_2SO_4	Sulfuric acid

Q	Swelling capacity
ϕ_w	Volume fraction of gelatinised starch
v/v	volume/volume
A_w	Water activity
WHC	Water holding capacity
W_S	Water in the saturated fibre
S	Water solubility index
w/w	weight/weight
w/v	weight/volume
wwb	Wet weight basis

LIST OF PUBLICATIONS AND CONFERENCES

Studies completed during candidature, some of which are reported in this thesis, have been published or presented in the following communications:

Peer-reviewed papers:

Allan K. Hardacre, Roger G. Lentle, Sia-Yen Yap, John A. Monro. (2018). Predicting the viscosity of digesta from the physical characteristics of particle suspensions using existing rheological models. Manuscript submitted to the Journal of the Royal Society Interface for publication.

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Conferences, seminars:

Hardacre, A., Lentle, R., Yap, S. Y., Monro, J. (2014). Functional fibres: Will they reduce carbohydrate digestion? Conducted oral presentation in NZIFST Annual Conference 2014 (1^{st}-3^{th} July, 2014), Christchurch, New Zealand.

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