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## The impact of diet on wastewater treatment works phosphorus loading

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### **Abstract**

Phosphorus (P) is a building block for life in which the human body requires 0.55 g of per day. In some cases, this requirement is exceeded by 2g per day, with P additives contributing to half of this exceedance. The use of P has become prominent as demand for processed convenience foods has increased. P can cause significant eutrophication once discharged to the environment. As of October 2019, 55% of assessed rivers and 73% of assessed lakes in England failed the current water quality standards. A survey was conducted to calculate the average P consumption of individuals who identify as meat eaters, flexitarians, vegetarians and vegans based on stated eating habits and reported P levels in foods, revealing an estimated P consumption of 1715, 1664, 1244, 1125 mg P/day respectively. It was estimated that current diets contribute 45% of the P load to wastewater treatment works (WwTW). If the UK population were to all convert to veganism this would decrease to 14% reducing the

load to WwTW by over 15,000 tonnes of P per year, or 9000 tonnes of P per year if there was a move towards a 50% vegetarian or vegan population. It was also found that individuals with a higher level of education were more likely to be vegan suggesting that to reduce P discharges to river, the population needs to be educated on what is in their food and the associated environmental impacts.

**Key words:** phosphorus; diet; source apportionment; wastewater; veganism

## 1 Introduction

Phosphorus (P) is a building block for life, being essential in the structure of RNA and DNA (Childers et al., 2011), making it a necessary component of any diet. The human body requires approximately 0.55g of P/capita/P/capita/day to carry out essential functions (Table S1 in the Electronic Supporting Information), however this intake is often exceeded (FSA, 2007), with an estimated 1g P/capita/day contributed by food additives alone, up 50% from the estimated 0.5g in 1990 (Zadeh et al., 2010). Food containing additives also comprises 70% more P than those without additives (Winger et al, 2012). Diet therefore contributes significantly to the estimated total of 2.3g of P/capita/day (including other sources such as dosed tapwater, detergents, food scraps etc) discharged to sewagewastewater treatment works (WwTW) (Comber et al., 2013).

Water bodies within the UK are governed by the Water Framework Directive (WFD, Directive 2000/60/EC) Urban Wastewater Treatment Directive (UWWTD, 91/27/EEC) and the Habitats Directive (Directives 92/43/EEC). The WFD has the aim of improving the chemical and ecological quality of the UK's water bodies. Eutrophication associated with P fluxes to surface waters has been recognised as a significant concern by the Environment Agency (EA, 2019). 5164 km of rivers, 96 lakes and reservoirs in England are formally recognised as being affected

by eutrophication caused by wastewater effluents and diffuse agricultural runoff (Bowes et al., 2010; White and Hammond, 2007). Phosphorus is present in many different forms in sewage and can become bioavailable during wastewater treatment prior to discharge to receiving waters (Miller and Hooda, 2011; Comber et al., 2015). Even though chemical dosing for P reduction is undertaken at around 700 WwTW in the UK (approximately 10% of all WwTW), responsible for the processing wastewater for around 24 million people, there is still a significant P discharge from WwTW effluent (typically 1 to 2 mg-P/l, although stricter permits as low as 0.1 mg-P/l are being introduced). This makes WwTW effluent along with agricultural runoff the most significant sources of P to the aquatic environment (DEFRA, 2002).

The process of managing and reducing inputs of P to waterbodies requires modelling to predict the efficacy of any mitigation methodologies. In order to complete the modelling accurately it is necessary to fully understand the sources of P to WwTW. With phosphorus in foodstuffs a key domestic source and significant contributor to the overall load to sewer, it is timely to assess the contribution of diet to P loads entering WwTW. The P consumed is found in 3 dietary sources: foods that contain P naturally (organic), food processed with P (inorganic) and dietary supplements containing P (Holliday, 2007). Around 60-70% of consumed P is absorbed in adults to maintain a healthy body (Bowman and Russell, 2001). Organic P found in meat is relatively easily digested by the gastrointestinal tract and around 40-60% is passed in the urine, whilst P found in plants, in the form of phytic acid (Figure S1), forms complex structures, which cannot be hydrolysed by the majority of organisms. Less than 50% of the total plant P is absorbed through digestion and is excreted in faeces rather than urine (Jonsson et al., 2004; Kalantar-Zadeh et al., 2010). Phosphorus used in additives, including that in cola-based drinks, is almost completely absorbed and excreted in urine (Valentine, 2006; Holiday, 2007; Winger et al., 2012).

Around 60% of P consumption in a normal diet can be attributed to milk, meat, fish and eggs; because sources of protein are typically sources of P (Figure S2) (Kremsdorf et al., 2013; USDA, 2001). A total of 20% of P can be found in cereals and legumes, less than 10% from fruits and 10% from P additives. Other constituents of diet such as tea, coffee, oils and spices only supply

minimal amount of P (Holliday, 2007). Multivitamins and supplements also present a significant contribution to P consumption levels (Calvo and Uribarri, 2013).

A key factor relating to the ingestion and excretion of phosphorus is the amount of P in protein and how much protein is consumed in different diets. The assumptions associated with these variables has a major bearing on the estimates of P loads to WwTW. On a weight by weight basis, it has been reported that plant protein contains approximately twice as much P than animal protein (Jonsson et al., 2004). It has been suggested that a plant based diet can increase the quantity of P excreted by up to 8% based on an Australian study, above current levels of P ingestion of 1.8 g/capita/day (Metson et al., 2016). Other reported P excretion rates for generic diets including meat and plant based protein range from 0.5 to 2.0 g/capita/day (Mihelcic et al., 2011) and more recently a range of 1.03 to 1.56 (median = 1.43) g/capita/day (Naden et al., 2016).

A recent UK study reported current excretion rates of 1.4 g/capita/day (Forber et al., 2020) and based on simply replacing animal based proteins with plant based ones suggested excretion rates could increase with a shift towards vegetarian and/or vegan diets. The study, however, based the P budget calculations on the substitution of all non-plant based protein with protein from legumes and beans. However, there is a flaw in this assumption because although there is more P in plant proteins on a gram per gram basis; vegans and vegetarians do not eat the same quantity of protein as omnivores. Typically meat eater consume 100 g of protein a day compared with around 79, 70 and 50 g per day for pescatarians, vegetarians and vegans respectively based on available reported data (Elorinne et al., 2016; Mariotti and Gardner, 2019; Bakaloudi et al., 2020). Consequently, in order to derive accurate estimates of P loads to WwTW, there are significant benefits in undertaking more empirical diet-based assessment of P ingestion and excretion and calculating P loads based on reported food consumed.

There is also a significant difference between the P content of processed foods compared with more natural diets. Phosphate salt additives are for flavour appeal, freshness and safety, where they act as an emulsion stabilizer to maintain the “juiciness” of the product by retention of moisture and avoidance of oxidation of metals within the meat (Table S2). The

use of P has become more prominent as demand for processed convenience foods has increased. Foods that are processed conventionally contain more P. The same food stuffs can contain significantly more P if processed (Table S3), With processed ham containing 65% more P mg/ kg than carved ham (Drummond, 2016). Leon (2013) found that 44% of best-selling grocery items in the US contained P additives (Table S4) and that these foodstuffs were typically cheaper and as such it is expected that lower income households (often less well educated) consume more P than the average. Reported data supports these assumptions (Bell et al., 1977) where 8 healthy students urinary P levels were tested after 1 month of low P consumption (0.98 g P/day) followed by a month of high P (2.1 g P/day) diets. The difference in the P levels were made by food additives in meats, cheese, breads, soft drinks, pies and some other foods. The urinary P was 0.43 g/ day under the low P diet and 1.01 g/ day for the high P diet. It was estimated that 51% of the P was absorbed from the gastrointestinal tract.

The number of vegans in the UK quadrupled between 2014-2019, from 150,000 to 600,000 (The Vegan Society, 2020). The vegetarian population of the UK is also significant with 1.2 million people following a vegetarian diet (The vegetarian Society, 2020). Studies have suggested that vegetarian diets contain significantly less P than omnivorous diets (Forber et al., 2020) (Table S5). Experiments where groups of people have consumed the same quantity of P but in differing forms have shown that consuming a vegetarian diet over the week resulted in significantly lower serum P levels compared with the individuals who consumed the meat-based diet (Moe et al., 2010 - Table S6). This demonstrates the higher bioavailability of P found in meat sources, which may also have implications during the wastewater treatment process via its distribution between the effluent and sludge phases, and so has commensurate impacts for the environment.

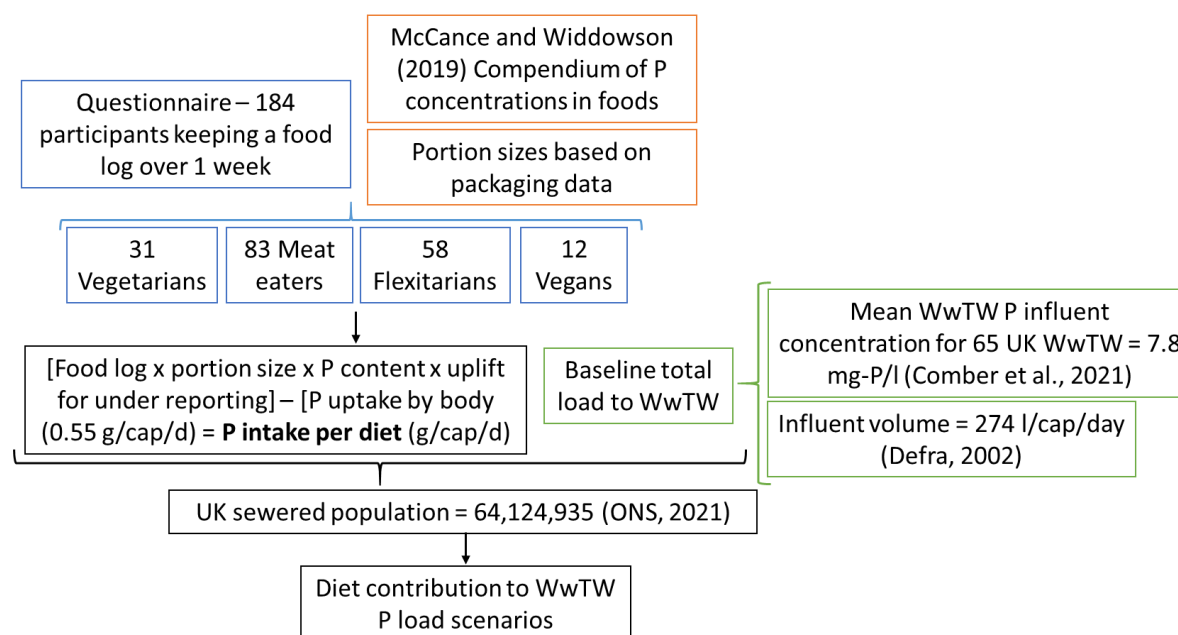
A more recent phenomena, at least in the UK, is the increase in the takeaway food market, which has continuously grown since 2009 with an increase of 3.5 billion GBP 2009-2020 to 10 billion GBP in 2017 (Just Eat, 2017). The market is utilised predominantly by young people driven by technological advances in online food ordering (Brophy, 2019). The COVID-19 pandemic has only served to increase the demand in takeaway food by up to 24% in people of the age 55 and over for example (CGA, 2020). Diet is not the only source of P to WwTW, particularly in the UK. Other sources to WwTW include tap water dosing where typically

between 1 and 2 mg-TP/l as orthophosphoric acid or sodium phosphate is added to meet WHO drinking water standards for lead (10 µg-Pb/l). It has been estimated there are 2709 tonnes of P discharges to UK sewers annually from this source (Comber et al., 2013) which is a common practise globally (Goody et al., 2017). When urine and faeces are added with food additives, 69% of total load can be apportioned to dietary factors (Comber et al., 2013). However, the sources and their magnitude do vary considerable over time reflecting changes in policy. For example other sources such as detergents contribute to the load, although P in phosphates (now replaced at least in part by phosphonates) was limited to less than 0.3g-P per standard dosage from laundry detergents in the UK in 2013 and in automatic dishwasher products in 2017.

This study for the first time quantifies the significance of P in additives and different forms of diet based on reported dietary intake rather than assumed simple replacement of protein sources of P which may over estimate actual P loads to WwTW. This approach allows the extent to which P consumption within diets, changing patterns of food consumption and subsequent excretion contributes to the P load to WwTW with commensurate impacts on discharges to surface waters.

## 2 Methodology

This study brought together datasets generated via an extensive diet questionnaire, a database for P in foods (McCance and Widdowson, 2019) combined with reported data for P loads to UK WwTW (Figure 1).



**Figure 1 Schematic of the methodology used to calculate loads of P from diet and its contribution to WwTW influent loads**

## 2.1 P in foods

All data for concentrations of P in food were abstracted from McCance and Widdowson (2019). The compendium provides a variety of composition data including P for over 1,200 foods consumed in the UK. All methods, by all laboratories used to determine concentrations were UKAS accredited (PHE, 2017). This dataset is the basis for the daily phosphorus intakes calculated in conjunction with the questionnaires and food diaries. The reported data doesn't take into consideration the bioavailability of P in each item, only listing the P concentration in the food and not how it would be absorbed, utilised and excreted.

## 2.2 Questionnaire analysis

Questionnaires were prepared using Google Surveys, and food diaries were compiled using Microsoft word and distributed via e-mail. Ethical considerations were made before questionnaires were distributed to participants, including the use of consent form detailing storage and use of data. In total 184 participants responded (83 meat eaters, 58 flexitarians, 31 vegetarians and 12 vegans, roughly mirroring the wider UK population's preferences. Each individual provided food diaries over 1 week for all food consumed. Demographic data on



age, gender, diet type and education were collected. The four dietary classification were used to quantify P load from WwTW's these can be defined as follows:

- **Meat eater:** Having no awareness of meat consumption and eating meat accordingly.
- **Flexitarian:** Having an awareness of how much meat is consumed and making choices to avoid it at times.
- **Vegetarian:** only consuming meat free products but still consuming animal products.
- **Vegan:** not consuming any form of animal product.

For every participant and every type of food consumed, recommended serving sizes taken from packaging were used unless otherwise stated by the participant. Totals were compiled and used to assess total loads of P to WwTW. Tonnes of P per year to WwTW was calculated using the average P consumption for each dietary classification determined through the questionnaires conducted, as well as the number of individuals in each classification for each scenario (Figure 1).

Under reporting is widely recognised in dietary surveys undertaken globally. This has been taken into account when calculating the P consumption. Participants often change their eating behaviours or omit items (ONS, 2016). The 'double labelled water' (DLW) technique is widely accepted as the most accurate way to estimate food consumption. The NDNS report of 2016 aimed to ascertain the difference between actual calorie consumption and reported calorie consumption. Estimates taken from self-reporting of energy intake (SREI) were found to be, on average, 32% lower than DLW measures of energy expenditure (EE). There was no difference between males (mean = 31%, standard deviation = 16%) and females (mean = 33%, standard deviation = 17%). Although it is recognised that calorie intake and P intake are not directly correlated as high calorie foods are not always high in P, an increase in calorie consumption in the majority of cases will result in an increase in P consumption (Bailey, 2018). Owing to this issue, the values produced for daily P consumption reported for this study were uplifted by 32% to compensate for under reporting in the questionnaires and food diaries.

To calculate the baseline load contribution of P in WwTW influent, the percentage of the population in each dietary classification needed to be determined. This was achieved using data from the "Food and You" survey conducted by the Food Standards Agency and the National Centre for Social Science Research (Natcen, 2019), combined with YouGov's data

noting 14% of the population identify as flexitarian. To quantify the load from WwTW through diet, the following Diet classification percentages were used: 1% vegan, 3% vegetarian, 14% flexitarian and 82% meat eater.

## 2.4 WwTW influent concentrations

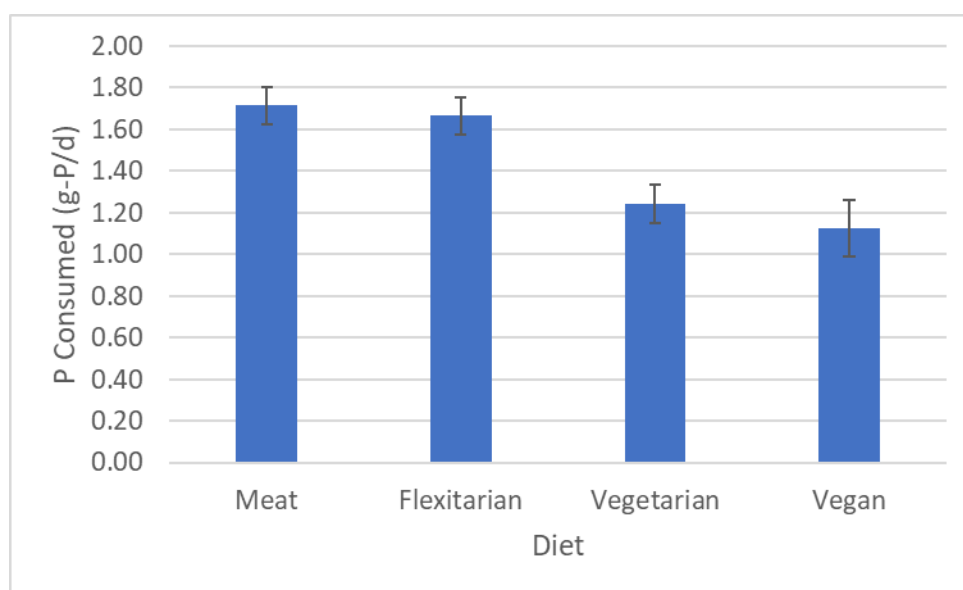
The Chemical investigation programme (CIP) in the UK was driven by the requirements of the WFD (UKWIR, 2018). The programme was designed to inform on the sources, removal and discharges of chemicals including P to the aquatic environment. Data was used to calculate loads of P to WwTW using flow and P influent (crude sewage) concentration from 65 WwTW (UKWIR, 2018). Samples were collected on up to 28 separate occasions across a one year period. The samples were collected in stainless steel samplers, stored in glass containers and transported at 4° C to the analytical laboratories. Analytical work was commissioned from contracted laboratories, who used their own in-house analytical methodologies, which were not standardised but had to meet a minimum and exacting performance criteria. Concentrations were determined using Inductively Coupled Plasma – Mass Spectrometry. To ensure analytical quality, the laboratories had to meet specific criteria. These included ISO17025 accreditation, the requirement to undertake tests of analytical performance to demonstrate that they met the stated programme requirements for limit of detection (LOD), precision and recovery in relevant sample matrices at relevant concentrations that is, proof of performance was required, rather than methods being stipulated. Further details are available elsewhere (Comber et al., 2018).

## 3 Results and Discussion

### 3.1 Questionnaire survey results

Figure 1 (Table S7) shows that individuals who eat less meat/animal products consume and therefore excrete less P and are younger on average. Statistically significant differences (95% confidence level) were apparent between vegetarian and vegan diets compared with those on meat and flexitarian diets. This is contrary to the data reported by Forber et al., (2020) owing to the way in which they substituted protein consumption between meat eaters and other diets purely on a like for like basis. The fact that there is almost twice the P content in plant-based proteins biased the estimate for P excretion. However, the data presented here, supported by statistics that show that vegans, in particular, tend to consume only half the protein of meat eaters (Elorinne et al., 2016; Mariotti and Gardner, 2019; Bakaloudi et al., 2020) meaning vegans excrete reduced P loads and in a less bioavailable form than meat eaters.

There is also a significant difference between the respondents age and eating habits, which is likely to reflect the impact of specific documentaries (Lockwood, 2018) and social media which is dominated by younger people (>50% are under the age of 34, Statista, 2020a).



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**Figure 1 Comparison of P consumption vs diet from the questionnaire data (brackets denote 95% confidence intervals) with 32% uplift to allow for under reporting of portions. No of individuals responding to the questionnaire were 83, 58, 31, 12 for meat eaters, flexitarians, vegetarians and vegans respectively**

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### 3.3 Calculated load to WwTW

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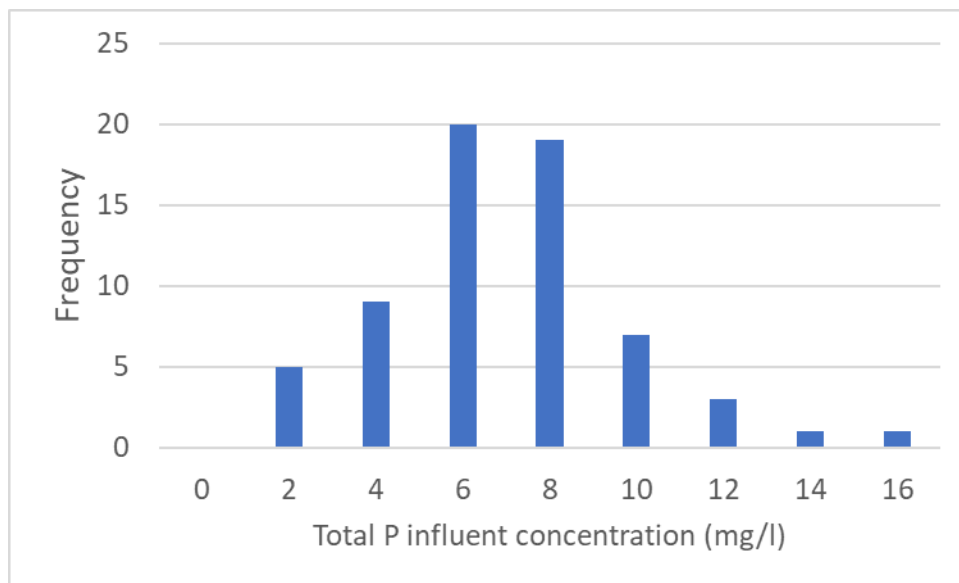
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To scale up predicted P loads to the UK as a whole, a per capita volume of water use per day was generated based on dividing the consented effluent flows from WwTW by the population served for 5771 WwTW across England, Wales and Scotland and taking the median value (274 l/cap/day – which includes rainwater runoff from roof and road as well as foul water from domestic, commercial and industrial premises). This was combined with population data using the sewerage network (96% - Defra, 2002) and the population of the UK (66,796,807 - ONS, 2020) generating a sewered population of 64,124,935 people and a volume to WwTW of 17.5 bn litres/day. From this data a baseline current load of P to UK WwTW could be generated by multiplying the volume by the mean WwTW influent concentration for 65 WwTW (Comber et al., 2021) for total P of 7.96 mg-P/l (Figure 2a). Using this approach provided a total influent load of 51,100 tonnes of P per annum, which was slightly greater than the 45,000 tonnes per annum reported previously (Comber et al., 2013), mostly reflecting the increasing population in the UK, as the mean influent concentration of total P was the same (8 mg-P/l). With a total load to WwTW calculated it was possible to determine the contribution from diet across a number of scenarios discussed below.



**Figure 2 Histogram of the P influent concentrations for 65 UK WwTW**

Dietary contributions to the loads of P to UK WwTW were calculated based on the results of the questionnaire survey for P consumption with an additional 32% contribution added to account for underreporting of food consumption in the questionnaires conducted within this study (Bailey, 2018). Then 550 mg/d of P was deducted to allow for P utilised by the human body for essential functions (Table S7). Using a combination of the measured baseline loads of P and the ratios of the population in each dietary classification (IPSOS Mori, 2016) combined with the average P excretion rate (Table 1), it was possible to calculate an estimated dietary contribution of P to the WwTW load. The per capita P intake loads were in line with those previously reported (Mihelcic et al., 2011; Metson et al., 2016; and Naden et al., 2016) with vegan consumption of P being 34% lower than meat eaters (Table 1). Allowing for the daily requirement for P, meant the reduction in excreted P was predicted to half for vegans compared with meat eaters.

**Table 1 Percentage of the total population categorised into the dietary classifications and the consequential contribution of diet to P loads in WwTW.**

Diet	g-P/capita/d		
	Mean daily P consumption rate <sup>1</sup>	+ 32% to allow for underestimation of portion size	P excretion rate (minus RNI) <sup>2</sup>
<b>Meat</b>	1.30	1.72	1.17
<b>Flexitarian</b>	1.26	1.66	1.11
<b>Vegetarian</b>	0.94	1.24	0.69
<b>Vegan</b>	0.85	1.13	0.58

<sup>1</sup> based on food diary and questionnaire data. <sup>2</sup> Reference Nutrient Intake (RNI) = 0.55 g-P/capita/day

Based on the available data, it was possible to run a number of scenarios regarding diet and impacts on loads to WwTW. For this study, seven scenarios were run explored (Figure 3 and Table 2):

- 1) Scenario 1 – Worst case of 100% of the population being meat eaters
- 2) Scenario 2 - Loads based on diet data generated from IPSOS data (considered the most accurate current situation)
- 3) Scenario 3 – Loads based on diet data generated from this study's questionnaire
- 4) Scenario 4 - Loads based on a best estimate of future eating habits
- 5) Scenario 5 - Loads based on a switch from meat to flexitarian diet
- 6) Scenario 6 - Loads based on a 100% switch to vegetarian diet
- 7) Scenario 6 – Best case of 100% of the population switching to veganism

As can be seen below, the current baseline dietary excretion estimates (as well as those derived from the questionnaire) lie within, but at the lower end of the range of other literature reported data (Naden et al., 2016).

**Table 2 Percentage of the total population categorised into the dietary classifications and the consequential contribution of diet to P loads in WwTW<sup>1</sup>.**

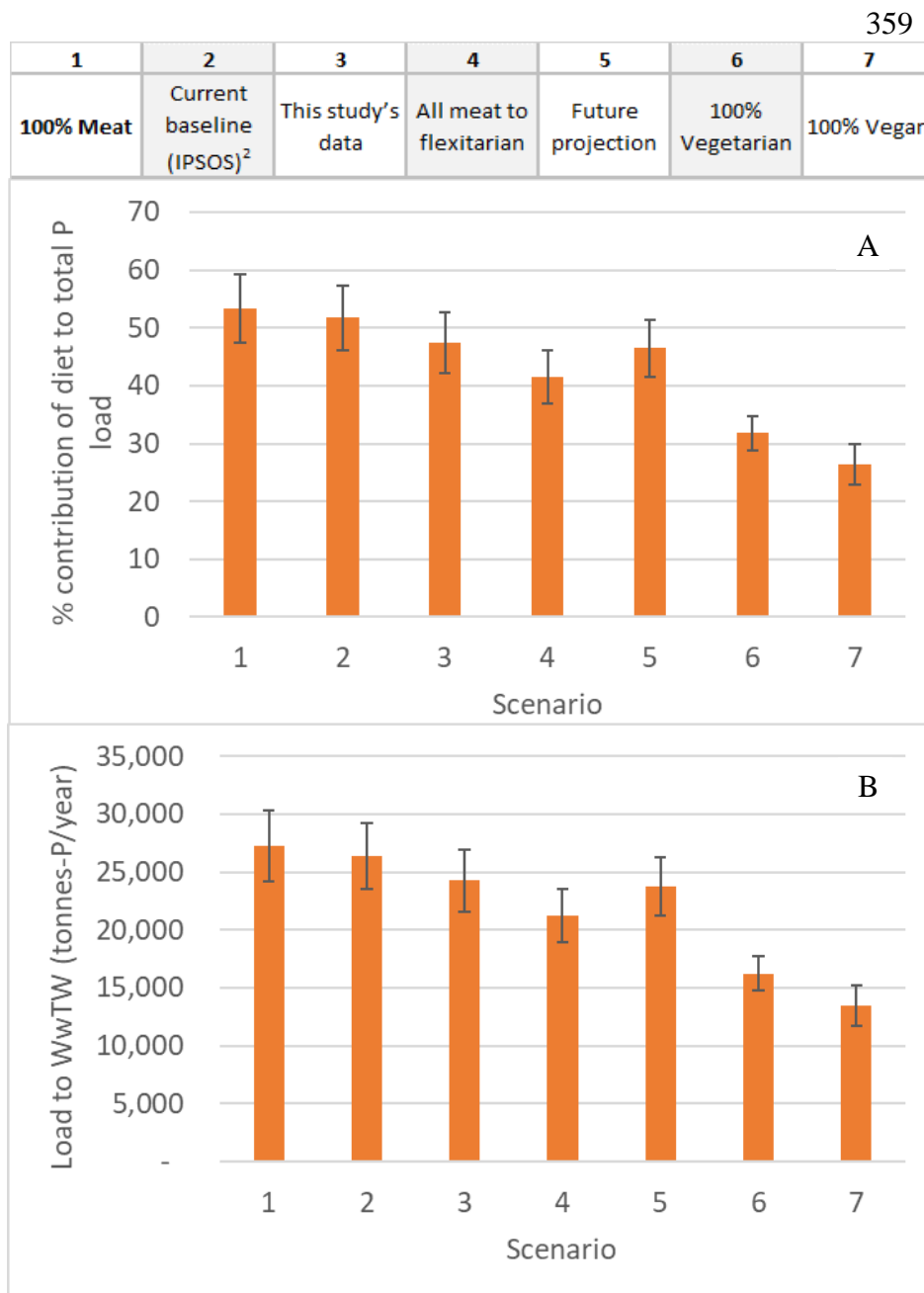
No.	Scenario	Diet Classification % of the population				Combined P excretion rate (g-P/capita/d)
		Meat	Flexitarian	Vegetarian	Vegan	
1	100% Meat	100	0	0	0	1.17
2	Current baseline (IPSOS) <sup>2</sup>	51	46	2.2	1.1	1.13
3	This study's data	45	32	17	6.5	1.04
4	All meat to flexitarian	0	77	17	6.5	1.01
5	Future projection	10	45	25	20	0.91
6	100% Vegetarian	0	0	100	0	0.69
7	100% Vegan	0	0	0	100	0.58
	Naden et al (2016) data					1.03 – 1.56

<sup>1</sup> includes an additional 32% reflecting under reporting of food consumption. <sup>2</sup> for dietary habits

These excretion rates can therefore be converted to loads received at WwTW based on scaling up using the number of people connected to the UK wastewater system. The current 'baseline' contribution of P from food was therefore calculated to be in the region of 27,000 tonnes per annum (Figure 3b), amounting to 53% of the total P load; the proportion from food increasing over the past few years owing to the removal of phosphates from household detergents. The loads derived from the questionnaire undertaken for this study, align well with the national survey, generating an estimated 24,000 tonnes per annum, slightly lower than the calculated baseline, reflecting the slightly higher proportion of vegetarians and vegans in the present survey used in the calculations. The questionnaire results showed a shift towards consuming less meat, this may be due to the demographic that filled out the questionnaire and/or the IPSOS Mori survey being conducted in 2016, which did not take account of the number of vegans quadrupling between 2014-2019 (The Vegan society, 2020). Shifting ideals and heightened awareness of the environmental impacts of personal consumption patterns are likely to be the cause of this (Bryant, 2019).

The estimates show that the current situation is close to the worst case owing to the limited difference between a flexitarian and all meat eating diet. The difference between a full meat or flexitarianism diet only has a 5% impact on loads equating to 2,690 tonne per annum of P.

However, a switch to vegetarianism would reduce loads to WwTW by 8,000 tonnes of P per annum (16% reduction) and in the unlikely event of the whole population switching to a vegan Diet, the load of P to WwTW would drop by 25%, equating to 13,000 tonnes of P per annum. A more realistic future scenario over the next 20 years derives a reduction from the current predicted load of 10% based on a drift towards vegetarianism and veganism; which still suggests a significant 5,000 tonnes of P per annum reduction in loads to WwTW (Figure 3).

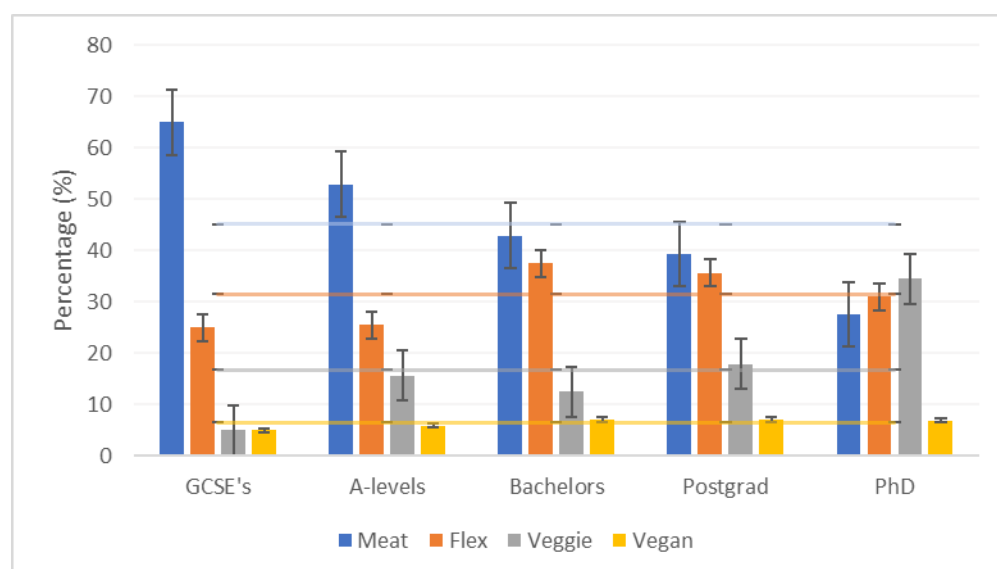


**Figure 3 Predicted dietary contribution of P loads to WwTW (A) and overall loads of P to WwTW from diet (B) (error bars denote 95% confidence intervals)**



### 3.4 Demographic data and impacts on P intake and excretion

Figure 4 shows the ratio of educational level between the dietary classifications. The solid horizontal lines represent the national percentage of each type of diet (IPSOS Mori, 2016) which are compared with data from the questionnaire. It can be seen that there is a higher ratio of meat eaters with only a secondary school level of qualifications (GCSEs) compared with those with A level, degree or post graduate degree qualifications as well. Conversely, there is an increasing trend in flexitarians and vegetarians with level of qualification. A growing trend towards higher education supported by the increasing number of vegetarians and vegans, therefore suggests that in the future, P loading to WwTW will reduce from domestic sources, owing to their lower-P diet.



**Figure 4** Percentage of questionnaire respondents from each educational background versus dietary classifications. Coloured horizontal bars represent the current mean % of UK population in each dietary classification.

However, there is a counterpoint to the increasing vegetable based diet, and that is the significantly increasing UK takeaway food sector, which has showed a £3.5 billion growth between 2009-2021 (Just Eat, 2017). Table 3 shows the significant difference in P content between common takeaways and roughly equivalent home cooked meals (average of 0.60 g P/100g and 0.34 mg P/100g respectively). Such a trend to higher P takeaway foods will therefore have a commensurate effect on P being discharged to WwTW.

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420 **Table 3** **P content of various takeaway meals (McCance and Widdowson, 2019).**

Item	P per portion (g)
<b>Takeaway meals</b>	
Pizza	1.04
Fish and Chips	0.70
Korma	0.58
Chow Mein	0.36
Big Mac	0.31
<b>Average (sd)</b>	<b>0.60 (0.30)</b>
<b>Home cooked meals</b>	
Chicken Pie	0.45
Spaghetti Bolognese	0.38
Chilli Con Carne	0.36
Cottage Pie	0.30
Bean casserole	0.226
<b>Average (sd)</b>	<b>0.34 (0.089)</b>

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422 The benefits of the higher likelihood of being vegan if you are young, could leading to a  
423 reduction in P entering WwTW, could therefore be largely negated by this generation also  
424 more likely to eat high P takeaway foods as they are often associated with meat consumption,  
425 although fast-food restaurants have recently introduced plant-based alternatives (PETA,  
426 2020). Consumers increasingly want to reduce their meat consumption but still buy products  
427 that mimic meat. It is often difficult for the average citizen to consume enough protein  
428 without also consuming too much P as they are inherently linked. Despite shifts in ideals, the  
429 food industry seems to be constantly moving with consumer requirements of convenience.  
430 With convenience comes P additives (Leon et al., 2020) and with the rise of ready meals and  
431 online food delivery particularly since the arrival of COVID-19, individuals are only set to  
432 consume more P. As discussed previously, similar food stuffs can contain varying amounts of  
433 P additives due to their intended shelf life (Gutiérrez, 2020). There is an increasing demand

for food on the go, with the market expected to grow £4.9 billion between 2019-2024, a 26.4% increase (IGD, 2019). Because of this, the use of P is likely to increase despite the increasing number of people switching to plant-based diets. Consuming fresher food is inherently more expensive and so individuals may not have the means to choose a more environmentally conscious product (Fairbrother, 2012). As shown by Drummond (2016), processed ham can contain nearly double the amount of P when compared with carvery ham (9.1 and 5.5 g-P/kg respectively). The first step in changing behaviour is changing attitudes. A survey by Bryant in 2019 questioned 1000 UK meat eaters, expressing their views about vegan and vegetarian diets, and their intended future consumption of meat. One in six intended on reducing their meat consumption in the next month.

## 4 Conclusions

Comber et al., (2013) reported that discharges to WwTW related to food and food additives contribute 68% of the load and therefore managing this source could lead to a decrease in P loads to rivers. The current prediction is 15% less which could be due to changing dietary patterns since the 2013 study as well as underreporting by participants in the questionnaires. The data presented here, shows the changing dietary patterns of West Europe (the UK and USA in particular) leads to significant shifts in loads of P excreted by the population and that shifting to plant based diets, with commensurately low levels of P additives, can lead a reduction in contribution of P loads to WwTW with a commensurate environmental improvement. Furthermore, with the banning of phosphate-based detergents in the UK, the contribution of diet to P loads to WwTW has commensurately increased, meaning that the benefits of reducing the consumption of foods containing P additives or shifting to a plant based diet would have significant benefits. However, our study also highlights the complexity in estimating trends owing to rapidly changing habits associated with education, increases in fast food consumption and shift towards plant based diets which are often conflicting in terms of P excretion rates. There are other benefits associated with plant-based diets, as they lead to less soluble, bioavailable P being excreted which would likely result in greater concentrations in the sludge rather than final effluents of WwTW.

This study has generated per capita loads of P excreted across a number of dietary scenarios. For future modelling purposes in terms of estimating the contribution of diet to P loads at WwTW and subsequent loads in effluents entering the environment a robust value of 1.13g of P/capita/day has been derived. With knowledge of trends in diet then this figure may be amended to plan for future phosphorus management. This research has highlighted the importance and significance of the assumptions used to estimate P loads to WwTW. The use of questionnaire based surveys for eating habits has provided empirical data regarding eating habits and P consumption. Differences in protein intake between types of diet mean it is not possible to simply substitute meat protein for plant-based protein in calculations. Significant reductions in P loads can be achieved by a shift in eating patterns. If the entire UK population were to go vegan, a saving of 13,000 tonnes of P per annum could be achieved. It is recognised that this is an unrealistic scenario due to meat eating being ingrained within society. However, more and more consumers are turning to plant-based lifestyles. If 50% of the population became vegetarian or vegan, a saving of at least 5,000 tonnes of P could be removed from WwTW influent loads per annum.

Planning forward, it is recognised that there is no hard and fast solution to reducing P loads in the UK; however changing attitudes and therefore behaviours are key in encouraging individuals to make the dietary shift. Significant investment is required both in education of consumers (through for example use of social media) and development of meat-based alternatives that are attractive to consumers. The food industry also needs to find preservative alternatives to P that cause less environmental damage. Without this, the rise of takeaways and convenience food could easily outweigh the natural shift to plant-based lifestyles.

## State of conflict of interest

The authors confirm that there are no conflicts of interest associated with this research.

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## Data availability statement

The data that support the findings of this study are available from the corresponding author, [Comber S], upon reasonable request.

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