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REVIEW ARTICLE

Nutritional contributions and processability of pasta made from climate-smart, sustainable crops: A critical review

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ABSTRACT
Total or partial replacement of traditional durum wheat semolina (DWS) by alternative flours, such as legumes or wholegrain cereals in pasta improves their nutritional quality and can make them interesting vector for fortification. Climate-smart gluten-free (C-GF) flours, such as legumes (bambara groundnut, chickpea, cowpea, faba bean, and pigeon pea), some cereals (amaranth, teff, millet, and sorghum), and tubers (cassava and orange fleshed sweet potato), are of high interest to face ecological transition and develop sustainable food systems. In this review, an overview and a critical analysis of their nutritional potential for pasta production and processing conditions are undertaken. Special emphasis is given to understanding the influence of formulation and processing on techno-functional and nutritional (starch and protein digestibility) properties. Globally C-GF flours improve pasta protein quantity and quality, fibers, and micronutrients contents while keeping a low glycemic index and increasing protein digestibility. However, their use introduces anti-nutritional factors and could lead to the alteration of their techno-functional properties (higher cooking losses, lower firmness, and variability in color in comparison to classical DWS pasta). Nevertheless, these alternative pasta remain more interesting in terms of nutritional and techno-functional quality than traditional maize and rice-based gluten free pasta.

KEYWORDS
Culinary properties; texture; digestibility; extrusion; lamination; functional ingredient

Introduction

Malnutrition (i.e., over and undernutrition) is a major public health problem worldwide. According to the Global Nutrition Report (2021), 2.2 billion people are overweight (body mass index between 25 and 30) of whom 772 million are obese (body mass index over 30). This reflects energy, but also macro and micronutrient imbalances. Indeed, modern diets are often too rich in empty calories, such as sugar and saturated fatty acids, and do not bring enough fibers, favoring type 2 diabetes, cardiovascular diseases, cancers, and other diet-related diseases. Besides overnutrition, FAO et al. (2022) reported that between 675 and 765 million of people were in hunger in 2020. Malnutrition leads to multiple micro and macro-nutrient deficiencies, such as iron, zinc, and protein. Between 20 and 25% of all deaths in adults have been associated with imbalanced diets in 2021 according to the Global Nutrition Report (2021).

Several public health strategies are adopted by countries to fight against malnutrition, such as food diversification, fortification, or optimization. National educational food programs promote diet modifications with a higher consumption of fruits and vegetables, nuts/seeds, whole grains, and unsaturated fat, coupled with a decrease in red meat, sugar, saturated fat, and salt consumption. There is also a recommendation to consume plant proteins instead of animal proteins. These recommendations can be found for instance in several national programs worldwide, such as the “Plan National Nutrition Santé” (PNNS) strategy in France (ANSES. 2016), the Food Based Dietary Guideline (FBDG-SA) in South Africa (Vorster, Badham, and Venter 2013) or the Dietary Guideline for Americans (DGA) in the USA (USDA 2020).

In addition to these public health actions, fortification has been chosen by some countries to improve the nutritional status of their population. Fortification is the voluntary or mandatory addition of one or more micronutrients (i.e., vitamins and minerals) in a staple food according to the World Health Organization (https://www.who.int/health-topics/food-fortification#tab=tab_1). Manufacturers can fortify their products according to the regulations in force in the country which control both the amounts of micronutrients that can be added to the product and the nature of the product to be enriched (Olson et al. 2021). Salt iodization which is a common practice around the world since 1920, vitamin A margarine fortification in Denmark, vitamin D fortification in milk in France, Spain or UK, folic acid enrichment in cereal products in Canada, USA, and

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Latin American countries are some examples of food fortification (OMS 2006). Depending on the country's laws, food industry can also improve the nutritional value of their products in terms of macro and micronutrients by adding new ingredients in the formulations or by using new processes to answer consumer demand. The reduction of saturated fatty acids, sugar, salt and the increase of plant-based proteins, fibers, and micronutrients are common in food process optimization. The addition of legumes in cereal-based products is one of the solutions to increase their fiber and micronutrient contents while improving their protein quantity and quality. Indeed, legumes are richer in protein than cereals and both ingredients have complementarity Essential Amino Acid (EAA) to reach the quality of animal proteins when they are used together in a well-balanced proportion (Vitz 2005). Legume enrichment in several staple cereal foods, such as bread, expended snacks, extruded ready-to-eat products, including pasta have been considered (Petitot, Boyer, et al. 2010; Yaver and Bilgiçli 2018; Pasqualone et al. 2020; Tas and Shah 2021).

Pasta is one of the most popular staple foods worldwide with a production of 16.9 million tons in 2021 according to the report of the international pasta organization (https://internationalpasta.org/annual-report/). Pasta are also an affordable and nonperishable product. Traditional pasta are made from durum wheat semolina (DWS) and water and have interesting nutritional quality as notably a high carbohydrate content (75 g/100g dry pasta) with a low glycemic index (GI, mean = 52) (reviewed in Atkinson et al. 2021) and a significant amount of protein (13 g/100g dry pasta) (Canadian Nutrition File = https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp). Pasta is, therefore a great vehicle for nutritional optimization. However, refined wheat lacks EAA, such as lysine and threonine (Abdel-Aal and Hucl 2002), and have a low fiber content of around 3 g for 100 g (Canadian Nutrition File).

The partial replacement of refined wheat semolina by non-conventional ingredients, such as fibers, vegetables or legume in pasta has been already attempted in order to improve their nutritional quality (reviewed by Bresciani, Pagani, and Marti 2022 and Sissons 2022) and notably both the quantity and quality of proteins, fibers and mineral content while keeping a low GI (Greffeuille et al. 2015; Berrazaga et al. 2020). Additionally, the rise in gluten hypersensitivity led to numerous studies of gluten free (GF) pasta (reviewed in Gao et al. 2017). The low nutritional values of GF traditional pasta made from rice or corn, especially in terms of protein quality and quantity, and glycemic response, has been solved in recent years by using 100% legume to formulate pasta (Laleg, Cassan, Barron, et al. 2016). The addition of new Raw Material (RM) in DWS pasta, although nutritionally interesting, modify their structure and negatively impact their technological and sensory properties, and therefore decrease their acceptance by consumers (Laleg et al. 2017). The addition of non-conventional ingredients in common GF pasta (corn and rice) which are already organoleptically far from traditional DWS pasta, could have less impact on the consumer acceptance.

The next step in this effort for pasta, or other staple food formulations could be to use crops that are both GF and resilient to diseases, such as mildew or fusarium wilt, and climatic hazards, especially droughts considering the increasingly scarce water. Some African crops, i.e., GF cereals, legumes, or tubers, can fulfill these conditions and have a higher nutritional value than wheat. From an agro-environmental point of view, legumes can fix the atmospheric nitrogen and therefore improve the nitrogen content in soil decreasing the need in chemical fertilizers. According to FAOSTAT (https://www.fao.org/faostat/fr/) legumes, such as cowpea, faba bean, chickpea, pigeon pea, and bambara groundnut are extensively produced in Africa (8 million; 1.5 million; 750,000; 800,000; and 240,000 tons in 2021, respectively). Cowpea, chickpea, and bambara groundnut are resistant to drought (Corp et al. 2004; Ngalamu, Odra, and Tongun 2015) and pigeon pea and bambara groundnut grow in a large variety of soils even the poorest, requiring only few inputs (Niyonkuru 2002). Similarly, millet, sorghum, teff, and amaranth are GF cereals or pseudo-cereals (i.e., amaranth) drought resilient and growing in poor soils. Conversely, corn, although the most produced cereal in Africa, has high water needs which does not make it an attractive RM in terms of sustainability (Emmambux and Taylor 2013). Cassava and sweet potato are drought- and diseases-resilient African root crops (203,572,940 and 29,972,001 tons in 2021, respectively FAOSTAT 2021) with a long shelf live making them interesting for food optimization. Although grown in Africa, these Climate-smart Gluten-Free (C-GF) crops are highly promising and could very likely extended elsewhere in the very near future.

In this context of climate and nutritional transition, the objective of this review is to study the overall nutritional potential of C-GF crops, considering their composition both in nutritional and anti-nutritional components, and to make an overview of their potential utilization in pasta production, considering their processing conditions, their textural, culinary, organoleptic properties and their potential nutritional properties, i.e., starch and protein digestibility. This review will concentrate on a subset of C-GF crops that present substantial production volume, resilience to drought, and adaptability to impoverished soils, i.e., sorghum, millet, teff, amaranth, chickpea, faba bean, cowpea, bambara groundnut, pigeon pea, orange fleshed sweet potato, and cassava.

Biochemical characteristics and nutritional quality of C-GF cereal, legume, and tuber flours

Biochemical characteristics, i.e., the quantity and quality of starch, proteins, lipids, fibers, micronutrients, such as iron, zinc, folic acid, and beta-carotene, and the presence of anti-nutritional factors of C-GF cereal, legume, and tuber flours are summarized in Tables 1A and 1B. As these new RM are used to replace wheat in pasta, biochemical characteristics of wheat flour or semolina are also presented in Tables 1A and 1B for comparison.

Table 1A. Biochemical characteristics of wheat and climate-smart gluten-free (C-GF) flours (macronutrients)

Raw material	Starch g/100 g d.b. (% amylose)	Proteins g/100 g d.b.	Chemical score (limiting AA)	PDCAAS	Lipids g/100 g d.b.	ω6/ω3	Fibers g/100 g d.b. (% insoluble fibers)	References
Wheat	71.8 (25%)	10.4–12.2	48 (Lys)	44–53 (IV-PDCAAS)	1.0–2.24	20.2	2.7–3.9 (48–75%)	Canadian Nutrition File (CNF); Gómez and Sciarini 2015; Bader Ul Ain et al. 2019; Millar et al. 2019; Stone et al. 2019; Vincent et al. 2020
Millet	69.9 (20–39%)	7.3–10.8	28 (Lys)	24 (IV-PDCAAS)	3.20–4.25	57.9	3.5–9.5 (83%)	CNF; Boye, Wijesinha-Bettoni, and Burlingame 2012; Emmambux and Taylor 2013; Vincent et al. 2020; Kurek et al. 2018
Teff	74.0–75.5 (20–30%)	9.4–13.3	60 (Lys)	/	2.38–4.40	6.9	8.0–9.8 (82%)	CNF; Zhu 2018; Gebru et al. 2019; Gebru, Sbhatu, and Kim 2020; Vincent et al. 2020
Sorghum	68.0 (20–30%)	8.4–10.4	43 (Lys)	19–29	1.70–3.34	21.8	4.7–6.9 (75%)	CNF; Anyango, de Kock, and Taylor 2011; Zhu 2014; Bader Ul Ain et al. 2019; Vincent et al. 2020
Amaranth	60.5 (25%)	14.4–17.5	99 (Leu)	32–36	6.48–7.80	47.0	3.3–15.1 (59%)	CNF; Martinez et al. 2014; Aguilar et al. 2015; Kurek et al. 2018
Bambara groundnut	50.2–52.9 (35%)	18.0–24.8	91 (Trp)	/	1.40–8.70	16.5	3.9–29.0 (95%)	Mune Mune et al. 2011; Adegunwa et al. 2014; Yao et al. 2015; Oyeyinka, Pillay, and Siwela 2019; Vincent et al. 2020
Chickpea	29.0–47.4 (29–34%)	16.1–23.6	85–104 (Met + Cys/Thr)	72–78 (IV-PDCAAS)	3.10–7.20	25.6	3.8–10.8 (55–81%)	CNF; EL Adawy 2002; Singh et al. 2004; Tavano et al. 2008; Tosh and Yada 2010; Stone et al. 2019
Cowpea	51.0–51.3 (17–26%)	20.7–26.3	110	80	1.12–2.27	1.7	5.0–16.1 (88–96%)	CNF; Garcia, I, and R 2010; Anyango, de Kock, and Taylor 2011; Emmambux and Taylor 2013; Naiker, Gerrano, and Mellem 2019; Vincent et al. 2020; Kewuyemi, Kesa, and Adebo 2021
Faba bean	38.1–57.6 (43%)	24.0–33.2	61–91 (Met + Cys or Trp)	56 (IV-PDCAAS)	0.90–2.20	17.3	11.7–27.5 (66%)	CNF; Laleg, Barron, Sante-Lhoutellier, et al. 2016; Çalışkantürk Karataş, Günay, and Sayar 2017; Millar et al. 2019; Setia et al. 2019; Stone et al. 2019; Vincent et al. 2020
Cassava	74.6 (20%)	1.6–3.0	50 (Leu)	/	0.61–0.70	/	3.9–4.3 (70%)	CNF; Mallillin et al. 2008; Johnson, Moorthy, and Padmaja 2010; Oladunmoye et al. 2014; Vincent et al. 2020
Sweet potato	60.9 (19%)	6.6–6.7	107	36	0.21	/	3.2–3.5 (75–97%)	CNF; Sun et al. 2012; Mu et al. 2017; Dereje et al. 2020

AA: amino acids; CNF: https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp; Cys: cysteine; d.b: dry basis; IV-PDCAAS: *in vitro* PDCAAS (if no specified = *in vivo* PDCAAS); Leu: leucine; Lys: lysine; Met: methionine; Thr: threonine; Trp: tryptophan.

Table 1B. Biochemical characteristics of wheat and climate-smart gluten-free (C-GF) flours (micronutrients and antinutritional factors)

	Iron mg/100 g d.b	Zinc mg/100 g d.b	Folic acid (DFE) µg/100 g d.b	Beta-carotene µg/100 g d.b	ANF	References
Wheat	1.43–4.99	0.50–1.56	240–344	0–2	123 mg phytic acids	CNF; Millar et al. 2019; Vincent et al. 2020
Millet	3.94–5.40	2.42–2.63	42–47	0	225 mg phytic acids	CNF; Vincent et al. 2020
Sorghum	3.14–3.50	1.63–1.78	25–32	0–1	528 mg phytic acids	CNF; Vincent et al. 2020
Teff	7.60–7.63	3.63	170	5	1520 mg phytic acids	CNF; Zhu 2018; Vincent et al. 2020
Amaranth	7.55	3.16	2449	0	400–410 mg phytic acids; 516–524 mg of phenolic compounds; 3.05–4.34 TIU/mg flour	CNF; Gamel et al. 2006
Bambara groundnut	1.40–16.64	1.06–6.78	100	0	710–1100 mg phytic acids; 0.96 mg tannins	Mune Mune et al. 2011; Adegunwa et al. 2014; Yao et al. 2015; Oyeyinka, Pillay, and Siwela 2019; Vincent et al. 2020
Chickpea	4.86–7.72	2.81–4.32	437	25	1210 mg phytic acids; 485.00 mg tannins	CNF; EL Adawy 2002
Cowpea	4.82–9.95	3.25–6.11	420–639	8–18	779–4540 mg phytic acids; 210.17 mg tannins; 29.65 TIU/mg flour	CNF; Ibrahim et al. 2002; Kewuyemi, Kesa, and Adebo 2021
Faba bean	5.00–6.70	1.83–4.18	260–423	29–32	889 mg phytic acids; 5.45 TIU/mg flour	CNF; Millar et al. 2019; Vincent et al. 2020
Pigeon pea	4.50–5.23	2.49–2.76	340–456	16–101	375 mg phytic acids	CNF; Onimawo and Akpojovwo 2006; Vincent et al. 2020
Cassava	0.59–2.00	0.17–0.74	59–100	0–17	154 mg phytic acids	CNF; Vincent et al. 2020
Sweet potato	2.28	1.27	47	36,036	5–15 mg phytic acids	CNF; Oboh, Ologhobo, and Tewe 1988

ANF: anti-nutritional factors; CNF: https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp; d.b: dry basis; DFE: dietary folate equivalent; TIU: trypsin inhibitor units.

Cassava has the lowest protein quantity (1.6–3.0%) with three to fifteen times less protein than other flours, followed by sweet potatoes (6.6–6.7%). Cereals as millet, sorghum, and teff have around two to five times less proteins than legumes, i.e., faba bean, cowpea, pigeon pea, and bambara groundnut (Table 1A). Teff has the richest protein content among the selected C-GF cereals with ~9.4 up to 13% of proteins. The protein content of the pseudo-cereal amaranth is an intermediary between cereal and legume protein values. Pseudo-cereals and legumes have 1.5–2.5 times more proteins than wheat. Besides their protein content, their composition in Amino Acids (AA) and in particular in Essential Amino Acid (EAA), is a key element of their quality. The protein Chemical Score (CS), indicator of its quality, is calculated as follows (equation 1 below): the amount of every EAA of the protein is compared with the recommended EAA pattern of the FAO (FAO 2011). The CS of the whole protein corresponds to the lowest EAA score, i.e., the limiting EAA in the considered protein.

$$\left(EAA\,CS = \frac{Amount\ of\ limiting\ EAA\left(g/100gprot\right)}{\mathrm{Re}commended\ amount\ of\ the\ same\ EAA\left(g/100gprot\right)} \times 100 \right) \tag{1}$$

A CS below 100 indicates that the protein is lacking at least one EAA. On the other hand, a CS of 100 and above indicates that the protein covers the needs in all EAA if the protein requirements are met. C-GF legumes (bambara groundnut, chickpea, cowpea, faba bean, and pigeon pea) and pseudo-cereal (amaranth) have CS very close or above 100, which is two to three times higher than C-GF cereals (millet, teff, and sorghum) and wheat (Table 1A). As for all cereals and legumes, the complementarity of EAA composition of C-GF cereals and C-GF legumes concerning lysine and sulfur EAA (methionine and cysteine) is noticed. Teff appears as an interesting cereal due to its high level of lysine and methionine compared to other C-GF flours.

In addition to CS, the bioavailability of EAA is an essential parameter to fully approach the nutritional quality of a protein diet. The Protein Digestibility Amino Acid Score (PDCAAS) allows to classify protein sources according to both their EAA profile and their protein digestibility (Boye, Wijesinha-Bettoni, and Burlingame 2012). A PDCAAS close or above 100 (or 1) is synonymous of great protein quality. Chickpea and cowpea have a two to four times higher PDCAAS than cereals and even pseudo-cereals (Table 1A). Their PDCAAS are also higher than other common legumes, such as common pea or lentils (Semba et al. 2021). Sweet potato and amaranth have high CS but low PDCAAS which can result in low bioavailability of their EAA (Table 1A).

Another difference between wheat flour and C-GF crops is the nature of their storage proteins. Wheat flour is composed of 20% of albumins and globulins and 80% of gliadins and glutenins (De Cindio and Baldino 2016). In GF cereals, such as sorghum, major prolamins are zein, kafirin, or pennisetin. In chickpea, cowpea, faba bean and pseudo-cereal (amaranth), storage proteins are mostly globulins (50–60%)

and albumins (10–30%) (Taylor et al. 2016; Foschia et al. 2017). These differences, notable in solubility, will have a direct impact on the ability of flours to make pasta (Petitot, Abecassis, and Micard 2009) (see next section).

In comparison with oilseeds, C-GF cereals, legumes, and tubers are not an important source of lipids (<7%). Among them amaranth, bambara groundnut, and chickpea are the richest with around 6% of lipids (Table 1A). In addition to quantity, lipid quality, i.e., the fatty acid profile and the unsaponifiable composition (liposoluble vitamins, phytosterols…) remains an important feature of the nutritional quality of flours. Some fatty acids of great interest are not synthesized by the human body, notably linoleic (LA, C18:2, ω6) and α-linolenic acid (ALA, C18:3, ω3) (ANSES 2011). In most of the diets omega 6 consumption is strongly higher than omega 3 and do not abide by the recommendations. For instance, in France ω6/ω3 ratio is close to 7 (ANSES 2017) far away from the FAO recommendation (2009), i.e., a ω6/ω3 ratio close to 4–5 for adults (Elmadfa and Kornsteiner 2009). Cowpea and teff have the lowest ω6/ω3 ratio with values of 1.7 and 6.9, respectively (Table 1A), which make them interesting from a lipid quality point of view. Other C-GF flours have very high ratio between 16.5 and 47 (Table 1A). ω6/ω3 ratio of tubers are not shown because of their very low lipid content (<1%).

Starch, made of amylose and amylopectin biomolecules, is one of the major constituents of cereals, legumes, and tubers. Cereals (millet, teff, and sorghum) and cassava have 1.2–2.4 times higher amount of starch than legumes, however faba bean, pigeon pea, chickpea, and bambara groundnut have higher amylose proportion (29–45%) than sorghum, teff, wheat and tubers (around 20–30%). Furthermore, cowpea have lower amylose proportion (17–26%) than other C-GF legumes (Table 1A). This difference of starch composition may affect the ability of flour to make pasta (Petitot, Abecassis, and Micard 2009) and starch digestibility (Thorne, Thompson, and Jenkins 1983) (see next section).

The consumption of high-fiber products is highly recommended (ANSES. 2016). The fiber quantity of flours (Table 1A) is highly variable for the same flour due to the different species and level of flour refining. C-GF flours have 2–10 times more fiber content than wheat flour. From the highest to the lowest we find legumes (faba bean, chickpea, pigeon pea, and bambara groundnut), pseudo-cereal (amaranth), cereals (millet, sorghum, and teff), and tubers (cassava and sweet potato). FAO recommends to consume more than 25 g of fiber per day (WHO/FAO 2003; EFSA 2010). However, in most of diets, fiber consumption is lower than this recommendation. For instance, in France, fiber consumption is 17.1–22.6 g per day (ANSES 2017), and 17.4–20.7 g per day in UK in adults (Public Health England 2018). The use of high fiber C-GF cereal and legume flours instead of wheat increases fiber content of food products and thus fiber intake. In terms of quality, two types of fibers, soluble and insoluble, are generally distinguished, which have various health effects as for instance slowing of transit time or stool-normalizing effect (Higdon 2004). C-GF cereals, bambara groundnut, cowpea, and sweet potato flours have a higher proportion of insoluble fibers (75–97%) compared to wheat flour (48–75%). Amaranth has a lower insoluble fraction with 59% of insoluble fibers. The quality of the fibers can be described even more precisely than soluble/insoluble (i.e., viscosity, fermentability) to have a better comparison between these RM, but there is still a lack of data available on this topic for C-GF.

Iron, zinc, folic acid, and beta-carotene amounts in C-GF flours are resumed in Table 1B. In a general way, C-GF legumes have higher micronutrients amounts than C-GF cereals and wheat. Indeed, bambara groundnut, chickpea, cowpea, and faba bean have 1.2 to 5 times more iron than millet and sorghum. All C-GF legumes have 4 to 25 times more folic acid than millet and sorghum (Table 1B). Wheat has the lowest micronutrient content (iron, zinc, and beta-carotene) among cereals except for folic acid. Pseudo-cereal (i.e., amaranth) and teff have higher micronutrient content than cereals but remains lower than legumes. Tubers are the poorest in micronutrients except for beta-carotene amount in orange fleshed sweet potato which is 300–1000 times higher than other RM, and folic acid content of cassava which is 1.3–5 times higher than millet and sorghum. There is large variability in the same RM due to the variety species studied and the refinement of flours.

Despite the interesting nutritional composition of C-GF flours, nutritional benefits can be impacted by the presence of anti-nutritional factors (ANF). There are several types of ANF, such as phytic acid, phenolic compounds (such as tannins, phenolic acid), enzyme inhibitors (protease, amylase inhibitors), saponins, and lectins (reviewed in Samtiya, Aluko, and Dhewa 2020). Phytic acid can complex metal ions, such as iron, calcium, and zinc decreasing their bioavailability and inhibit the activity of digestive enzymes (reviewed by Samtiya, Aluko, and Dhewa 2020). Tannin by complexing with protein can affect protein digestibility (reviewed in Samtiya, Aluko, and Dhewa 2020). Protease (e.g., trypsin inhibitor) and amylase inhibitors also decrease protein and starch digestibility by blocking the enzyme receptor sites. Milling and pasta process can largely decrease the amounts of some ANF, such as tannins and trypsin inhibitor activity (TIA), respectively. Laleg et al. (2017) reported a decrease of TIA from 7.84 to 2.28 mg/g between faba bean flour and cooked pasta. On the other hand, phytic acid was not affected by pasta process and remained to be monitored. In C-GF flours, bambara groundnut, chickpea, cowpea, and faba bean are richer in phytic acid than sorghum and millet, and even more than tubers with around 1 g/100 g of flour against <600 mg/100 g (Table 1B). Moreover, teff has the highest phytic acid content of C-GF cereals with 1520 mg/100 g, which is 3–7 times more than other cereals, and pigeon pea has two times less phytic acid content than other C-GF legumes. All C-GF legumes and cereals have more phytic acid than wheat, which can alter their nutritional benefit. Regarding TIA, cowpea has a high amount, i.e., 6–10 times more than in faba bean and amaranth flours. It is possible to limit the impact of some ANF, especially phytic acid and enzyme inhibitors with flour pretreatment methods, such as soaking, germination, or fermentation (reviewed by Samtiya, Aluko, and Dhewa 2020). Thermal treatments as autoclaving and cooking used during process can also decrease ANF and especially TIA content of RM (reviewed by Samtiya, Aluko, and Dhewa 2020).

Techno-functional, culinary, and organoleptic qualities of pasta made from C-GF cereal, legume, and tuber flours

Pasta process and overview of parameters that define their qualities

Pasta is traditionally made from DWS by successive hydration and mixing, low-temperature extrusion (<50 °C), or sheeting and drying steps. This last step can be done at low (LT, 50–55 °C), high (HT, 60–80 °C), or very high (VHT, >80 °C) temperatures to reach a moisture of 12% in the final pasta (Manthey and Twombly 2005). There is no drying step in the case of fresh pasta. After these different steps, the pasta is ready to be cooked. The structure of DWS cooked pasta is described by Resmini and Pagani (1983) as "a compact fibrillary network of coagulated proteins that envelops the gelatinized granules." It is obtained throughout the different process steps. During the extrusion or sheeting step, starch granules are trapped in the newly formed gluten network due to mechanical forces (reviewed in Petitot, Abecassis, and Micard 2009). Drying step strengthens the micro- and macro-structure by disulfide bond formation in the protein network in a higher extent with HT and VHT drying. The last changes occur during the cooking step with the starch gelatinization and protein coagulation (reviewed in Petitot, Abecassis, and Micard 2009).

Pasta quality can be approached by several parameters, such as Cooking Loss (CL), firmness, color, and overall sensory qualities that describe the techno-functional and organoleptic properties of pasta. A firm and elastic pasta, an absence of stickiness and low CL are synonymous with good pasta quality (Abecassis, Faure, and Feillet 1989). Color has also a great influence on consumer preference and should be take into account to describe pasta qualities. It is linked to the intensity of the Maillard reaction involving both free amine residues from proteins and reducing sugars, thus reducing the bioavailability of lysine (Cubadda and Carcea 2003). This reaction takes place mainly during the drying step, and especially with HT and VHT drying (75 and 85 °C respectively) (Resmini and Pellegrino 1994).

Overview of pasta made from C-GF flours

Formulation, process, culinary, and organoleptic properties of pasta made from C-GF legume, cereal, and tuber flours are summarized in Tables 2–4, respectively. For each C-GF flour, the data are ranged according to pasta formulation: 100% C-GF flour, C-GF flour/wheat, and C-GF flour/GF flour (classical GF as rice or corn, or other C-GF flour). The pasta process and the methods used for their characterization impacting their properties, the comparison between studies will only be made considering their variation to the pasta control used in each corresponding study (i.e., 100% wheat flour or GF pasta in most of the studies). The comments will therefore be on improvement or alteration of the pasta qualities due to incorporation or use of C-GF flours in pasta.

Amaranth, chickpea, and millet pasta are more studied than bambara groundnut, cowpea, pigeon pea, and teff based pasta (Tables 2 and 3). C-GF flours are used in mixture with DWS or with rice or corn flour in ~50 and 30% of pasta studied, respectively. Only 20% of studies look at pasta made from 100% C-GF cereals, legumes and tubers. A wide range of DWS replacement by C-GF flours has been studied. Around 25% of DWS based formulations contained <10% of C-GF flours, and <15% of DWS based pasta contained more than 50% of these flours. Regarding the addition of C-GF flours in GF pasta, formulations with 10% maximum represent <15% of the studies against 30% for the formulations including more than 50% of C-GF flours. C-GF legumes, cereals, or tuber based pasta are processed like basic DWS pasta by LT extrusion for 70% of them. LT drying, which preserves the nutritional qualities of the pasta, is widely used (85% of the pasta) in studies on C-GF flour-based pasta. In the next part, the addition of C-GF flours is first discussed in DWS pasta, then in GF pasta, followed by 100% C-GF flour pasta.

Impact of the partial replacement of DWS by C-GF flours

Several studies have already focused on the partial or total substitution of refined DWS by whole wheat, GF cereals, or legume flours in pasta. Adding alternative flours leads to biochemical changes in protein, starch, or fiber compositions (quantity and/or quality) which affects the pasta structure and thus its quality. Gluten contained in wheat flour is a major factor in the textural and culinary properties of pasta particularly because of its viscoelasticity and its ability to form disulfide bonds during drying and cooking steps. The addition of new proteins dilutes the gluten network and leads to lower pasta qualities (Laleg et al. 2017). Petitot, Barron, et al. (2010) reported that the lower sulfur AA content in legume compared to wheat flour increases the proportion of weakly linked proteins in detriment to covalently and notably S-S linked proteins in cooked pasta (Laleg et al. 2017; Laleg, Greffeuille, et al. 2019). These molecular changes and their impact on its quality parameters as resilience and CL are linearly correlated to the increase of legume flour from 0 to 100% in pasta (Laleg et al. 2017). The increase in CL observed by these authors is in accordance with results obtained by several authors with partial or total replacement of DWS by C-GF flours in pasta (Tables 2–4). Increase of 20–100% of CL is reported depending on the level of DWS substitution by the C-GF flour. The presence of higher amounts of fibers in C-GF flours compared to DWS (Table 1A) may also explain the increase of CL. In fact, the presence of fibers can disrupt the protein matrix continuity and lead to a higher penetration of water in pasta during cooking. For instance, the addition of 50% of whole pearl millet in DWS pasta has resulted in 40% increase of CL, and 50% of increase for a total replacement

Table 2. Resume of textural, culinary and organoleptic properties of climate-smart gluten-free (C-GF) legume based pasta

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
Bambara groundnut flour							
Bambara groundnut + wheat flour	Whole bambara groundnut flour + whole wheat flour (20:80) + 1% salt	Extruded; HT drying at 80 °C − 2 h	6.95%	/	Raw L* = 51.79 a* = − 4.99 b* = 13.57	57 consumers of pasta 6.65/9.00	Oyeyinka et al. 2021
		Sifted (500, 350, 300, and 112 µm) Bambara groundnut flour; Extruded; HT drying dried at 80 °C − 2 h	4.5–8.45%	/	Raw L* = 52.11–54.78 a* = − 4.74 to − 3.48 b* = 13.57–16.62	5.51–7.68/9.00	
Chickpea flour							
100% Chickpea flour	Chickpea flour	Extruded 25 °C 80 bar single layer; dried at 55 °C − 8 h	7.4%	TA (No information) 8.3 N	Cooked L* = 62.3 a* = 6.7 b* = 39.0	/	Suo et al. 2022
	Chickpea flour	Laminated; dried at 45 °C − 4 h	13.02%	TA (10 kg load cell. 50% compressed) 1.47 N	/	/	Garcia-Valle et al. 2021a
	Chickpea flour + 34.3% egg whites	Rest during 1 h after hydration; Laminated; HT drying at 100 °C − 8 min	3.09%	/	/	100 untrained testers 7/9	De Lima, Botelho, and Zandonadi 2017
Chickpea + wheat flour	Chickpea flour + DWS (2.5:97.5; 5:95; 7.5:92.5; 10:90)	Extruded (spaghetti); no drying information	3.88–5.79%	TA (5kg load cell) 12.60–22.13 g	/	15 testers (27–51 y) 7–8/9	El-Sohaimy et al. 2020
	Black chickpea flour + WS (7:93)	Extruded 50 °C; dried at 55 °C − 8 h	5.73%	TA (1 mm/s; 30% deformation) 4.89 N	Cooked = L* = 44.18 a* = − 7.14 b* = 14.16	/	De Pasquale et al. 2021
	Chickpea flour + DWS (13.5:86.5)	No coarse fraction; Extrusion 45–50 °C; dried at 55 °C	4.60%	TA (1 mm/s; 30% deformation) 7.34 N	Cooked = L* = 65.5 a* = 0.8 b* = 18.5	/	Schettino, Pontonio, and Rizzello 2019
	Chickpea flour + DWS (10:90; 15:85; 20:8; 25:75; 30:70)	Dehulled chickpea flour; spaghetti; Extrusion; no drying information	4.5–4.84%	TA (No information) 510–672 g	Raw = L* = 53.96–57.25 a* = 6.25–8.28 b* = 33.76–38.74 Cooked = L* = 71.26–75.85 a* = 3.42–6.52 b* = 27.03–30.61	/	Wood 2009
	Chickpea flour + DWS (50:50)	Laminated; dried at 45 °C − 4 h	8.48%	TA (10 kg load cell. 50% compressed) 2.07 N	/	/	Garcia-Valle et al. 2021a

(*Continued*)

Table 2. Continued.

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
	Chickpea flour + DWS (20:80; 40:60; 60:40; 80:20)	Laminated; dried at 45 °C – 4 h	7.01–10.84%	TA (10 kg load cell. 50% compressed) 1.79–2.59 N	/	/	Garcia-Valle et al. 2021a
	Fermented chickpea flour + WS (17:83)	Fermentation in 30 °C tap water; Extruded 50 °C; dried at 55 °C – 8 h	5.80%	TA (1 mm/s; 30% deformation) 4.8 N	Cooked = L* = 46.57 a* = − 1.67 b* = 12.78	/	De Pasquale et al. 2021
	Fermented chickpea flour + DWS (13.5:86.5)	No coarse fraction; Fermentation in 30 °C water; Extrusion 45–50 °C; dried at 55 °C, duration not know	5%	TA (1 mm/s; 30% deformation) 4.6 N	Cooked = L* = 65.6 a* = 0.3 b* = 22.9	/	Schettino, Pontonio, and Rizzello 2019
Chickpea + other flour	Chickpea flour + pea flour (40:60)	Commercial pasta «La bona Usanza»	12.48%	/	/	15 subjects 5.2–5.8/7.0	Turco et al. 2019
	Chickpea flour + (white corn flour + rice flour (ratio 3:2)) (25:75; 50:50; 75:25)	Heat treated corn and rice flour; Extruded 25 °C 80 bar, single layer; dried at 55 °C – 8 h	5.9–7.4%	TA (No information) 8.8–10.3 N	Cooked = L* = 65.1–71.9 a* = 0.9–5.1 b* = 25.5–33.9	/	Suo et al. 2022
	Chickpea flour + Rice flour (10–30:70–90)	30 min rested after hydration; Cooking extrusion (90, 100 and 70 °C in the 3 sections; 60, 80, 100 rpm); Dried at 40 °C during 4 h to reach 12% pasta moisture	4.37–5.93%	TA (double compression up to 50% of sample volume) 207.0–277.5 N	Raw = L* = 69.97–71.61 a* = − 0.56 to −3.74 b* = 36.54–39.04	15 subjects 5.33–6.07/9.00	Bouasla, Wójtowicz, and Zidoune 2017
	Chickpea flour + Tiger nut flour (50:50) + pre-gelatinized Tiger nut flour (0–10%) + 13% fresh eggs	20 min rested after hydration; Laminated; dried at 55 °C, RH = 60% during 5 h 30 to reach 10–12% of pasta moisture	8.7–12%	TA (AACC method 16–50 0.17 mm/s until total deformation) 6.2–8.8 N	/	/	Martín-Esparza et al. 2018
	Chickpea + Tiger nut flour (50:50) + Fenugreek (replacement of 0–10% of TNF) + 11% eggs	20 min rested at 4 °C after hydration; Laminated; fresh pasta	5.9–7.3%	TA (AACC 16–50; 50% compression; 1 mm/s; 5 kg load cell) 25.3–31.1 N	Raw = L* = 46.3–48.6 a* = 8.72–9.47 b* = 26.1–26.9 Cooked = L* = 53.8–60.7 a* = 4.4–4.8 b* = 17.9–20.0	40 untrained testers 3.4/7.0	Llavata, Albors, and Martin-Esparza 2019
Cowpea flour							
Cowpea + wheat flour	Cowpea flour + Soft red winter wheat flour (10:90; 20:80; 30:70)	Decorticated cowpea; Extruded; HT drying : 40 °C – 1 h + 80 °C – 2 h + 40 °C – 2 h	/	/	Raw L* = 49–53.6 a* = 2.2–3.2 b* = 15.0–17.5	25-member consumer panel 4.0–4.5/7.0	Bergman and Weber 1994
Faba bean flour							
100% Faba bean flour	Faba bean flour	Dehusked faba bean; Extruded; dried at 55 °C during 12 h to reach 11% pasta moisture	14.35%*	TA (AACC 66–50; 0.17 mm/s) 4.37 N	Raw = L* = 38.7 a* = 9.1 b* = 19.5	/	Laleg, Barron, Sante-Lhoutellier, et al. 2016
	Faba bean flour	Dehusked faba bean; Extruded; dried at 55 °C to reach 12% of moisture	13–15%*	/	/	43 consumers (19–69 y) 3.72	Laleg et al. 2017
	Faba bean flour	Dehusked faba bean; Extruded; HT drying: 90 °C to reach 12% of moisture	8–10%*	/	/	3.67	

(*Continued*)

Table 2. Continued.

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
	Faba bean flour	Dehusked faba bean; Extruded; dried at 55 °C, RH = 92 to 72%, to reach 12% of moisture	14.4%*	/	/	/	Laleg et al. 2021
	Faba bean flour	Dehusked faba bean; Flour heat treatment 60 min 90 °C Extruded; dried at 55 °C, RH = 92 to 72%, to reach 12% of moisture	26.2%*	/	/	/	
	Faba bean flour	Dehulled faba bean; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture	10.8%	TA (294 N load cell. 1 mm/s; compressed at 70% of the initial thickness) 172 N	Raw = L* = 52.4 a* = 4.2 b* = 20.3	/	Rosa-Sibakov et al. 2016
	Fermented faba bean flour	Dehulled faba bean; Fermentation 30 °C 48 h; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture	11.8%	/	Raw = L* = 42.6 a* = 11 b* = 12.9	/	
	Faba bean flour + TG	Dehulled faba bean; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15h to reach 12% of moisture	11.3%	199 N	Raw = L* = 48.7 a* = 3.9 b* = 17.7	/	
	Fermented faba bean flour + TG	Dehulled faba bean; Fermentation 30 °C 48 h; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture	10.3%	243 N	Raw = L* = 42 a* = 11 b* = 12.5	/	
Faba bean + wheat flour	Faba bean flour + WS (62:38)	Extruded; dried 55 °C − 15 h	8.7%	TA (1 mm/s; compressed at 70% of spaghetti thickness) = 3.48 N	/	/	Berrazaga et al. 2020
	Faba bean flour + DWS (35:65)	Dehulled faba bean; Extruded; dried 55 °C to reach 12% moisture	6.8%	TA (1 mm/s; compressed at 70% of spaghetti thickness) = 0.055 N/mm (graphic)	Raw = L* = 60.7 a* = 7.3 b* = 40.7 Cooked = L* = 61 a* = 2.2 b* = 18.3	/	Petitot, Boyer, et al. 2010
	Faba bean flour + Wheat flour (10:90; 20:80; 30:70)	Dehulled faba bean; Immersion in boiling water during 3 min before milling; Extruded, 60 rpm, 40–42 °C; dried at 40 °C − 16 h, RH = 40%	7–9%	/	/	/	Giménez et al. 2012

(*Continued*)

Table 2. Continued.

Formulation	Process	Results				References
		Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	
Faba bean flour + WS (10:90; 30:70; 50:50)	Dehulled faba bean; Extruded 45–50 °C; dried at 55 °C, duration not know	5.22–7.79%	TA (1 mm/s; 30% deformation) 2.89–4.01 N	Cooked = L* = 58.02–63.35 a* = −2.65 to −2.05 b* = 19.66–28.79	/	Rizzello et al. 2017
Fermented faba bean flour + WS (10:90; 30:70; 50:50)	Dehulled faba bean; Fermentation 30 °C during 24 h; Extruded 45–50 °C; dried at 55 °C, duration not know	5.91–7.96%	TA (1 mm/s; 30% deformation) 2.77–3.86 N	Cooked = L* = 57.03–59.77 a* = −2.23–3.78 b* = 37.85–43.69	/	
Faba bean flour + WS (35:65; 70:30)	Dehusked faba bean; Extruded; dried at 55 °C to reach 12% moisture	8–12%*	/	/	43 consumers (19–69 y) 3.95	Laleg et al. 2017
	Dehusked faba bean; Extruded; HT drying : 90 °C to reach 12% moisture	5–9%	/	/	/	
Faba bean flour + DWS (35:65)	Dehulled faba bean; Extruded; HT drying: 70 °C to reach 12% moisture	5.8%	TA (1 mm/s; compressed at 70% of spaghetti thickness) = 0.075 N/mm (graphic)	Raw = L* = 58.7 a* = 11.0 b* = 46.8 Cooked L* = 59.2 a* = 4.1 b* = 19.6	/	Petitot, Boyer, et al. 2010
	Dehulled faba bean; Extruded; HT drying: 90 °C to reach 12% moisture	5.9%	0.12 N/mm (graphic)	Raw = L* = 41.1 a* = 21.5 b* = 28.0 Cooked = L* = 45 a* = 10.2 b* = 22.4	/	
Faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled; Extruded 50 °C; dried 55 °C – 16 h, RH = 50%	≈5%	/	Raw = L* = 84.6–85.7 a* = −1.84 to −1.19 b*=14.2–17.7 Cooked = L* = 81.5–83.6 a* = −1.42 to −1.19 b* = 15.7–17.5	/	Tazrart et al. 2015
		/	TA (method AACC 1999; 1 mm/s; 2 g trigger force) 10.2–15.9 N	/	2.2–2.4/5.0	Tazrart et al. 2019
Faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled; Extruded 50 °C, fresh pasta	/	TA (method AACC 1999; 1 mm/s; 2 g trigger force) 8.1–17.1 N	/		

(*Continued*)

Table 2. Continued.

	Formulation	Process	Results				References
			Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	
Faba bean + other flour	Faba bean flour + Corn flour (30:70)	Dehulled faba bean; Extrusion cooking (single screw, 100 °C, 60 rpm); dried at 40 °C, RH = 40%, during 16 h	9.07%	/	/	/	Gimenez et al. 2016
	Faba bean flour + Corn flour (30:70)	Dehulled faba bean; Extrusion cooking (single screw, 80, 90 or 100 °C); dried 40 °C, RH = 40%, during 16 h	9.07–16.33%	/	/	/	Gimenez et al. 2013
Pigeon pea flour							
Pigeon pea + wheat flour	Fermented Pigeon pea flour + DWS (5:95; 10:90; 12:88)	Fermentation = 42 °C – 48 h in distilled water; 15 min rested after hydration; Extruded (single screw); pre-dried ambient temperature for 1h and dried at 50 °C – 2 h	6–8%	/	/	19 semi-trained members 5.48–8.68/15.00	Torres et al. 2006
Pigeon pea + Other flour	Pigeon pea + Brown rice (10–30:70–90)	Cooking extrusion (30, 40, 50, and 70 to 110 °C in the 4 sections, respectively, twin screw); dried 50–60 °C, duration not know	6.11–11.19%	TA (load cell 50 kg; 1 mm/s; distance 2 mm; 0.5 N force) 7.22–15.06 N	Raw = L* = 43.10–55.21 a* = 0.60–2.00 b* = 8.13–14.50	/	Rafiq, Sharma, and Singh 2017

DWS: durum wheat semolina; Extruded: low temperature extrusion; HT: high temperature; RH: relative humidity; TA: texture analyzer; TG: transglutaminase; WS: wheat semolina.
*Difference between dry matter of dried and cooked pasta.

(Jalgaonkar, Jha, and Mahawar 2018b). Torres et al. (2006) even reported that only 5% of pigeon pea addition in DWS pasta leads to a 50% fiber content and to 100% increase of CL. CL are not the only quality parameter to be impacted by the partial or total replacement of DWS by C-GF flour.

The addition of C-GF legumes, cereals, and tubers to DWS pasta often decreases firmness of pasta compared to 100% DWS from 10 to 40% decrease with 30 to 50% of C-GF flour addition. Martinez et al. (2014) reported a decrease from 10 to 20% of pasta firmness with the addition of 40 and 50% of amaranth in DWS pasta. 30% of DWS replacement by sorghum flour results in a 15% decrease in firmness. These results are in accordance with Wood (2009) and Tazrart et al. (2019) who found around 20 and 30% of firmness decrease with the addition of 30% of chickpea and faba bean in DWS pasta, respectively. Addition of tubers, such as sweet potato also leads to 40% firmness decrease with 40% replacement in DWS pasta (Saleh, Lee, and Obeidat 2018). Tazrart et al. (2019) explained that the weakness of protein network of legume enriched pasta leads to a higher disruption of starch granules during gelatinization. Combined with the higher amount of fibers, this decreases the firmness of these pasta. At the opposite, some authors as Petitot, Boyer, et al. (2010) reported an increase of 25% of firmness with 35% of faba bean in DWS pasta. This can be due to finer particles size of flour used (Petitot, Boyer, et al. 2010). Indeed, sieve of 1000 and 500 µm were used for chickpea and faba bean flour in Wood (2009) and Tazrart et al. (2019) studies instead of 100 µm for Petitot, Boyer, et al. (2010). The use of larger-mesh sieves leads to an increase of particle size and increases fiber content, which can be responsible to protein network disruption and thus a decrease of firmness. Moreover, Tazrart et al. (2019) and Petitot, Boyer, et al. (2010) work with two different types of faba bean pasta, namely maccheroncini and spaghetti, respectively. This can also be responsible of firmness differences between the two studies due to differences in thickness (Suo et al. 2021).

Color is also impacted by C-GF flour addition in DWS pasta with a significant decrease of 6–30% of the pasta lightness L* with 15–50% of C-GF flour addition (Tables 2–4). The dark color of C-GF flours compared with wheat semolina is linked to a higher presence of bran, ash, and pigments (Islas-Rubio et al. 2014; Rosa-Sibakov et al. 2016). Redness is also affected by all C-GF flours with an increase in a* value (Bergman and Weber 1994; Islas-Rubio et al. 2014; Gull et al. 2015; Rizzello et al. 2017). This increase can result of the Maillard reaction. Bergman and Weber (1994) showed a 40% increase of a* value with 30% of cowpea addition in wheat pasta compared to 100% wheat pasta. The use of HT and the higher level of lysine in cowpea flour compared to wheat may have favored Maillard reaction. Moreover, the higher presence of carotenoids in C-GF flours leads also to an increase of a* and b* (yellowness) values (Bergman and Weber 1994; Cabrera-Chávez et al. 2012). Rizzello et al. (2017) and Gull et al. (2015) reported a 35 and 400% increase of a* value with the addition of 30% of faba bean and millet in DWS pasta, respectively. The addition of cowpea, amaranth, cassava, and orange

Table 3. Resume of textural, culinary and organoleptic properties of climate-smart gluten-free (C-GF) cereal and pseudo-cereal based pasta

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
Amaranth flour 100% Amaranth Flour	Amaranth flour + 11.9% fresh egg (of AF)	Extruded; dried at 42 °C at least 9 h	8.45%	TA (5 kg load cell; 0.1 mm/s) 0.31 N	/	/	Schoenlechner et al. 2010
	Amaranth flour + 3% egg white/soy protein/casein (of AF)		7.55% (egg) 9.03% (soy) 13.55% (casein)	0.35–0.59 N	/	/	
	Amaranth flour + 1.2% DGM/DATEM (of AF) + 15% egg white (of AF)		6.51% (DGM) 8.8% (DATEM)	1.88–3.28 N	/	/	
	Amaranth flour + 9% eggs + 1.2% DGM	Laminated; 95 °C/RH = 91% drying – 45 min	11.5%	TA (5 kg load cell; 0.1 mm/s; force threshold 0.01 N) 0.84 N	Raw: L* = 54.9 a* = 1.9 b* = 32.2 Cooked: L* = 53.1 a* = 2.1 b* = 32.9	/	Islas-Rubio et al. 2014
Amaranth + wheat flour	Whole amaranth flour + bread wheat flour (15:85; 30:70; 40:60; 50:50) + 1% salt	Laminated + pre-dried at 30 °C during 30 min (40% RH) and dried at 30 °C for 17 h (65% RH)	6.6–7.9%	TA (twice compression; 0.5 mm/s) 37.0–44.4 N	Cooked: L* = 62.7–66.3 a* = 2.0–5.3 b* = 17.0–20.5	/	Martinez et al. 2014
	Amaranth flour + refined wheat flour (31:69; 39:61; 47:53; 54:46) + 28.32% eggs + 0.98% salt	Laminated; fresh pasta	/	/		56 untrained tasters (17–57 y) 4.77–6.02/9	Santos et al. 2015
	Amaranth flour + DWS + Dried amaranth leaves (50:50/0; 35:65/0; 55:45/5; 35:65/4; 35:65/8; 55:45/0; 70:30/0) + fresh egg (15.06–15.31%) + CMC (8.52–14.13%)	Extruded; dried at 80 °C – 4 h	6.93–10.15%	/	No information: L* = 55.0–92.34 a* = −1.89–8.09 b* = 29.65–40.29	50 potential consumers 1.26–3.84/4	Cárdenas-Hernández et al. 2016
	Amaranth flour + DWS (25:75; 50:50; 75:25) + 9% eggs + 1.2% DGM 1.2%	Laminated; 95 °C drying – 45 min	9.2–11%	TA (load cell 5kg; 0.1 mm/s; force threshold 0.01 N) 1.08–1.17 N	Cooked L* = 52.1–59.5 a* = −0.3–2.3 b* = 32.6–33.4	/	Islas-Rubio et al. 2014

(*Continued*)

Table 3. Continued.

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
Amaranth + other flour	Whole amaranth flour + Rice flour (25:75)	Extruded; dried 50 °C – 14 h	7.5%	TA (No information) 3.1 N	/	/	Cabrera-Chávez et al. 2012
		Pre-treated flour in a two zone extrusion-cooker (2 min; 120 °C. single screw); pasta making in extruder; dried at 50 °C – 14 h	4.5–7.5%	TA (No information) 5.3–7.2 N	/	/	
	Amaranth flour (15–50% of flour) + quinoa flour + buckwheat flour + egg white (0–12% of flour) + emulsifier (1.2 or 6% of flour)	Extruded; dried at 42 °C at least 9 h	5.48–7.45%	TA (5 kg load cell. 0.1 mm/s) 2.37–3.91 N	/	/	Schoenlechner et al. 2010
	Amaranth flour + Rice flour + Buckwheat flour (5:5:90; 15:5:80; 5:15:80; 15:15:70; 10:10:80) + 31.8% eggs + 2% XG	Laminated; 90 °C – 6 h (quality analyses) or 55 °C – 24 h for further analysis	5% AF = 14.12 – 15.04% 15% AF = 6.01–10.12% 10% AF = 12.85%	/	Raw: L* = 65.67–67.7 a* = 3.59–4.16 b* = 12.89–15.59	/	Rosa, Prestes, and Crauss 2015
	Amaranth flour + Pre gelatinized cassava flour (cassava starch + cassava bagasse 70:30) + CS (10:40:50; 10:20:70; 20:10:70; 30:20:50; 30:10:60;20:20:60) + 2% urucu/annato + 48% eggs	Laminated; dried 40 °C during 60 min to reach 10% of pasta moisture	/	TA 16.50 AACC 2000 (5 kg load cell; 0.17 mm/s. 1000 g compression force) 3.0–4.5 N	/	/	Fiorda, Soares, et al. 2013
	Amaranth flour + Pre gelatinized cassava flour (cassava starch + cassava bagasse 70:30) + CS (20:10:70) + 2% urucu/annato + 48% eggs	Laminated; 40 °C during 60 min (with water flask) + 60 °C during 30 min (without water flask) to reach 11–12% pasta final moisture	0.4%	/	/	50 non-trained tasters 7.2/9	Fiorda, Soares Júnior, et al. 2013
Millet flour							
100% Millet Flour	Pearl millet flour (different particle size)	Extruded; dried 50 °C – 2 h	No pasta integrity after cooking				Jalgaonkar, Jha, and Mahawar 2018b
	Pearl millet flour (different particle size)	Extrusion cooking 70 °C; dried 50 °C – 2 h	No pasta integrity after cooking				Jalgaonkar and Jha 2016
	Proso millet flour + GG (0–2%)	Dehulled Proso millet; Extruded; dried at room T° – 24 h	/	TA (compressed 75%; 5 mm/s) 42.81–44.80 N	Cooked = L* = 76.87–77.27 a* = −1.54–1.60 b* = 15.84–16.04	/	Motta Romero et al. 2017
	Proso millet flour + XG (0–2%)		/	56.42–42.47 N	Cooked = L* = 78.23–78.51 a* = −1.94–1.95 b* = 14.8–14.92	/	
	41–46 g Millet flour+ 16 g potato starch + 0.2 g salt + 0.8 g GG + 28 g liquid eggs	Decorticated millet; Laminated; Fresh pasta	2.11–4.82%	TA (AACC 66-50.01; 5 kg load cell; 10 mm/s) 3.64–10.31 N	Raw = b* = 33.42–39.38 Cooked= b* = 25.82–31.36	/	Cordelino et al. 2019

(*Continued*)

Table 3. Continued.

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
	Depigmented pearl millet	Depigmentation = soaked in 2% citric acid 48 h 37 °C; Extruded; dried at 60 °C – 3 h	10.14%	TA (1 mm/s) 2.08 N	Cooked = L* = 43.12 a* = 2.56 b* = 15.51	15 panel members (28–55 y) 3.08/10.00	Manoj Kumar et al. 2019
	Depigmented PM + sodium caseinate (10 and 20% of PM flour) + TG		10.34–12.2%	TA (1 mm/s) 1.99–3.22 N	Cooked = L* = 38.01–44.05 a* = 2.81–3.58	3.24–6.04/10.00	
	Depigmented PM + sodium caseinate with whey (10 and 20% of PM flour) + TG		5.99–7.61%	TA (1 mm/s) 1.97–2.26 N	Cooked = L* = 43.48–48.98 a* = 2.23–2.53 b* = 14.25–17.08	3.24–6.12/10.00	
Millet + wheat flour	PM flour + Wheat flour (10:90)	Soaked millet grain before milling; Extruded; dried 60 °C during 45 min to reach 7–8% moisture	1.43%	TA (50 kg Load cell; 2 mm/s) 23.8 N	Raw = L* = 60.1 a* = 5.0	No information 8.2	Yadav et al. 2014
	Whole PM flour + WS (50:50)	Extruded, twin screw; dried 50 °C during 2 h to reach 8–9% of final moisture	7.56%	TA (1 mm/s; 50% compression) 9.95 N	Raw = L* = 38.56 b* = 17.82	/	Jalgaonkar, Jha, and Mahawar 2018b
	FM flour + DWS (10:90; 20:80; 30:70; 40:60; 50:50)	Extruded (single screw); dried 60 °C, RH = 65% during 3 h to reach 8% moisture	15.2–24.4%	TA (50 kg load cell; 2 mm/s; 50% compression) 2.87–3.88 N	Raw = L* = 58.78–71.75 a* = 3.41–6.05 b* = 12.19–13.64 Cooked = L* = 43.86–57.69 a* = 3.71–6.24 b* = 9.97–11.04	/	Gull et al. 2015
	PM flour + DWS (10:90; 20:80; 30:70; 40:60; 50:50)		13.6–17.2%	2.14–3.12 N	Raw = L* = 70.92–76.52 a* = 0.07–0.70 b* = 12.81–15.40 Cooked = L* = 59.83–68.47 a* = – 0.38–0.87 b* = 12.71–13.85	/	
	Foxtail millet flour + Wheat flour + Green pea flour (30:60:10; 40:50:10; 50:40:10; 60:30:10) + 0.2 g salt	Extruded; dried at 60 °C – 3 h	/	TA (1 mm/s; compressed at 80% thickness) 9.66–9.70 N	Raw = L* = 67.1–74.9 a* = 4.0–4.7 b* = 15.0–16.6 Cooked = L* = 55.4–57.1 a* = 1.7–1.8 b* = 7.14–9.47	10 testers 7.9–8.8/9.0	Bhuvaneswari 2021
	PM flour + Wheat flour (10:90) + vegetables (23.8–25.9 g/100 g flour)	Soaked millet grain before milling; Extruded; dried 60 °C during 45 min to reach 7–8% moisture	1.02–1.31%	TA (50 kg Load cell; 2 mm/s) 26.7–37.3 N	Raw = L* = 47.9–61.3 a* = – 0.43–12	No information 7.9–8.5	Yadav et al. 2014
	FM flour (5–20% of flour) + PM flour (7.5–30% of flour) + Wheat flour + Composite flour (WS and carrot pomace 96:4) + CMC (2–4%)	Extruded (single screw); dried 60 °C, during 3–4 h to reach 9% moisture	5.03–8.4%	TA (10 mm/s; 5 kg load cell) 1.45–3.7 N	Cooked = L* = 50.10–59.83	15 Semi-trained testers 6.1–8.1	Gull et al. 2015

(*Continued*)

Table 3. Continued.

	Formulation	Process	Results				References
			Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	
	FM flour + WS (10:90; 20:80; 30:70)	Extruded (single screw); HT drying : 75 °C – 4 h	4.98–8.9%	/	Raw = b* = 5.95 (20:80)	15 testers 5.9–7.4/9.0	Krishnan and Prabhasankar 2010
	FM flour + WS + banana flour 15:70:15		6.75%	/	Raw = a* = 3.35 b* = 5.97	6.9/9.0	
	PM flour + WS (50:50)	Extrusion cooking, twin screw extruder; dried at 50 °C during 2 h to reach 8–9% moisture	7–10.4%	TA (1 mm/s; 50% compression) 6.5–11.4 N	/	/	Jalgaonkar et al. 2019
	Whole PM flour + WS (90:10; 80:20; 70:30; 60:40; 50:50; 40:60; 30:70; 20:80; 10:90)	Different particle sizes; Extrusion cooking 70 °C, twin screw, 120rpm; dried at 50 °C – 2 h	6.41–8.63%	TA (1 mm/s; 50% compression) 8.28–16.37 N	Raw = b* = 14.9–20.9	/	Jalgaonkar and Jha 2016
	PM flour + WS (50:50)	Extrusion cooking 70 °C; dried 50 °C to reach 8–9% moisture	8.06%	TA (1 mm/s; 50% compression) 9.9 N	No information L* = 38.37 a* = 1.71 b* = 16.12	No information 7.67/9.0	Jalgaonkar, Jha, and Mahawar 2018a
	PM flour + WS (50:50) + Defatted soy flour (5–10–25%)		8.11–9.22%	13.07–14.43 N	No information L* = 45.53–60.45; a* = 1.76–2.15; b* = 11.59–13.18	7.08–7.75/9.00	
	PM flour + WS (50:50) + Carrot powder (5–10–15%)		8.25–11.9%	8.17–9.7 8N	No information L * = 47.57–48.72; a * = 5.95–10.03; b * = 16.28–18.72	6.70–7.58/9.00	
	PM flour + WS (50:50) + Mango peel powder (5–10–15%)		8.11–9.91%	4.41–5.78 N	No information L* = 40.6–43.75 a* = 4–4.17 b* = 11.92–12.35	6.00–7.42/9.00	
	PM flour + WS (50:50) + Moringa leaves powder (3–5–8%)		8.13–10.05%	7.19–11.73	No information L* = 39.54–46.13 a* = 0.09–0.28 b* = 12.4–14.5	5.58–7.40/9.00	
	Depigmented whole PM + WS (50:50)	Depigmentation : grain soaked in 0.2 N HCl for 18 h (28–32 °C) Extruded, twin screw; dried at 50 °C during 2 h to reach 8–9% of moisture	7.22%	TA (1 mm/s; 50% compression) 9.37 N	Raw = L* = 52.89 b* = 21.38	/	Jalgaonkar, Jha, and Mahawar 2018b
Millet + other flour	Whole PM flour + barley flour (90:10; 80:20; 70:30) + whey protein concentrate (5–20% of PMF) + CMC (2–4% of PMF)	Soaked of whole PM flour in water until 30% moisture; Extruded; dried at 60 °C during 60–65 min to reach 8–9% moisture	7.53–9.54%	TA (5 kg load; 10 mm/s; 11% compression) 26.4–35.72 N	No information L* = 39.4–45.78	30 untrained testers 6.2–7.7/9.0	Yadav et al. 2012
Sorghum flour							
100% Sorghum flour	White sorghum flour + 11% egg albumen + 8.6% egg powder + 17.7% pre-gelatinized starch	Dehulled sorghum; Extruded; dried first at 40 °C – 30 min and 40 °C – 17 h RH = 75%	5.76%	TA (load cell 500 N. 50 mm/min and 0.085 N trigger force) = 46.42 N	/	25 semi-trained panelists 4.5/9.0	Palavecino et al. 2017
	Brown sorghum flour + 2.5% XG + 11% egg albumen + 5.7% egg powder + 1% pre-gelatinized starch		5.38%	55.3 N	/	3.8/9.0	

(*Continued*)

Table 3. Continued.

	Formulation	Process	Results				References
			Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	
Sorghum + wheat flour	Whole sorghum flour + WS (50:50; 60:40; 70:30; 80:20)	Extrusion cooking 55 °C, single screw; dried at 60 °C overnight	7.41–9.36%	/	/	15 semi-trained panelists 3.8–4.5/5.0	Benhur et al. 2015
	Whole red or white sorghum flour + DWS (20:80; 30:70; 40:60)	10 min rested after hydration; Laminated; dried at room temperature (21/25 °C) during 30 h to reach <10% moisture	4.48–5.93%	TA (load cell 25 kg; 1.0 mm/s speed; trigger force of 0.05 N) = 55–60 N (graphic)	Raw = L* = 57.88–63.57 (R) 61.05–64.16 (W) a* = 4.04–6.62 (R) 1.94–2.26 (W) b* = 17.93–20.58 (R) 15.91–20.73 (W) Cooked= L* = 58.38–64.62 (R) 61.09–65.22 (W) a* = 3.63–5.6 (R) 1.59–2.29 (W) b* = 13.64–17.51 (R) 12.95–18.33 (W)	50 untrained panelists (20–57 y) 5.34–6.56/9.00	Khan et al. 2013, 2014
Sorghum + other flour	Whole sorghum flour + Rice flour + Corn flour + potato starch (40–60:0–30:0–20:10–40) + eggs + oil (proportion not know)	Extrusion; dried 50 °C – 60 min and 60 °C – 30 min	0.85–1.10%	/	/	12 trained panelists (20–50 y) 4.2–5.5/9.0	Ferreira et al. 2016
	White sorghum flour + Parboiled brown rice flour + pre-gelatinized rice flour (15:60:25)	Extrusion 50 °C; dried at 50 °C – 14 h	8.4%	TA (load cell 2.5 kN; 0.67 mm/s speed) 192 N	Raw = L* = 81 a* = 2.5 b* = 16.3	/	Marengo et al. 2015
	Fermented white sorghum flour + Parboiled brown rice flour + pre-gelatinized rice flour (15:60:25)	Fermentation; Extrusion 50 °C; dried at 50 °C – 14 h	7.6%	183 N	Raw = L* = 79 a* = 2.5 b* = 16.9	/	
Teff flour 100% Teff Flour	Whole teff flour + 5% GG	30 min rested after hydration; Extruded; dried at 57 °C – 3 h	/	/	/	62 panelists 1.87/5.00	Kahlon and Chiu 2015
	Teff flour + 11% egg white powder + 1.1% emulsifier	Hydration with 50 °C water; Extruded; Fresh pasta	4.06%	TA (AACC method 16–50; 0.17 mm/s) 4.52 N	Cooked = L* = 62.32 a* = 1.63 b* = 15.62 Raw = L* = 57.98 a* = 2.96 b* = 19.10	22 trained panelists (22–44 y) 4.6/9.0	Hager et al. 2012, 2013

AF: amaranth flour; CL: cooking loss; CMC: carboxyl methyl cellulose; CS: cassava starch; DATEM: diacetyl tartaric acid ester of monoglycerides; DGM: distilled mono glycerides; DWS: durum wheat semolina; Extruded: low temperature extrusion; FM: finger millet; GG: guar gum; HT: high temperature; OA: overall acceptability; PM: pearl millet; R: red sorghum flour; RH: relative humidity; TA: texture analyzer; TG: transglutaminase; W: white sorghum flour; WS: wheat semolina; XG: xanthan gum.

Table 4. Resume of textural, culinary and organoleptic properties of climate-smart gluten-free (C-GF) tuber flour based pasta

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
Cassava flour							
100% Cassava flour	Cassava flour	Hydration with 40 °C water; Extruded (spaghetti); no drying information	24.2%	TA (50 kg load cell) 51.46 g	Raw = L* = 96.27 a* = −11.53 b* = 30.34 Cooked = L* = 88.16 a* = −9.74 b* = 30.15	/	Rachman et al. 2019
	Yellow/White cassava flour	Peeled cassava; Hydration with boiling water; Extruded; dried at 65 °C – 12 h	1.74% (W) 1.58%(Y)	No information 12.70 N (W) 13.34 N (Y)	/	/	Lawal, van Stuijvenberg, et al. 2021
	White or Yellow cassava flour	Hydration with boiling water; Extruded; dried at 65 °C	1.8–2.3%	TA (method 16–50 AACC 2000. 5 kg load cell; 2 mm/s; 90% of deformation) 12.2–13.2 N	Raw = L* = 70 (Y) 81.2 (W) a* = 1.2 (Y) 1.5 (W) b* = 15.1 (Y) 11.4 (W)	/	Lawal, Sanni, et al. 2021
Cassava + wheat flour	Cassava flour (half pre-gelatinized) + Hard wheat flour (50:50) + 1% egg	Extruded; dried at 45 °C	0.71%	/	Raw = L* = 73.5 a* = −3.62 b* = 37.15 Cooked = L* = 78.51 a* = −5.23 b* = 27.52	30 semi-trained posgraduate students 4.67/7.00	Odey and Lee 2019
	Cassava flour (half pre-gelatinized) + Wheat flour (50:50) + 1% egg	Fermentation 12, 36 or 60 h at 25 °C in tap water; Extruded; dried at 45 °C	0.96–1.17%	/	Raw = L* = 65.88–75.27 a* = −1.36 to −2.02 b* = 27.87–30.09 Cooked = L* = 76.8–79.83 a* = −4.54 to −3.62 b* = 22.26–26.08	4.33–5.87/7.00	
Cassava + other flour	Cassava flour + banana flour (75:25; 50:50; 25:75)	Hydration with 40 °C water; Extruded (spaghetti); no drying information	21.96–28.75%	TA (50 kg load cell) 58.78–61.90 g	Raw = L* = 86.33–90.65 a* = −8.31 to −6.02 b* = 30.2–31.64 Cooked = L* = 77.96–78.50 a* = −6.32 to −5.00 b* = 26.91–28.76	/	Rachman et al. 2019
	Cassava flour + banana flour (25:75) + egg white protein (5–15%)	Hydration with boiling water; Extruded (spaghetti); no drying information	3.80–7.35%	TA (5 kg load cell; 3 mm/s) 103.44–242.73 g	/	/	Rachman et al. 2020
	Cassava Flour + banana flour (25:75) + soy protein (5–15%)		7.64–10.6%	62.45–140.93 g	/	/	
	Yellow/white Cassava Flour + amaranth leaf powder (95:5)	Extruded; dried at 65 °C – 12 h	1.38% (Y) 2.5% (W)	No information 14.74 N	/	/	Lawal, van Stuijvenberg, et al. 2021
	White or Yellow cassava flour + fluted pumpkin powder (85–90:5–10)	Hydration with boiling water; Extruded; dried at 65 °C	0.8–2.6%	TA (method 16–50 AACC 2000. 5 kg load cell; 2 mm/s; 90% of deformation) 10.4–11.8 N	Raw = L* = 52–58.5 (Y) 53.4–61.7 (W) a* = −6.4 to −6.7 (Y) −0.1 to −0.2 (W) b* = 26.2–27.1 (Y) 14.2–15.5 (W)	/	Lawal, Sanni, et al. 2021
	Cassava Flour + amaranth flour (62–71:38–29) + CMC (0.21–0.25%) + 2.1% egg + enzyme Veron (1000U)*	Peeled cassava; Laminated; dried at 55 °C – 4 h	/	TA (50 kg load cell; 2 mm/s) 1.84–5.02 N	Raw = L* = 74.93–79.51 a* = 3.33–5.59 b* = 16.57–20.42	6 trained tasters (40–55 y) 2/5	Ramirez et al. 2019

(*Continued*)

Table 4. Continued.

			Results				
	Formulation	Process	Cooking loss (residues after evaporating the cooking water)	Firmness	Color	Overall acceptability	References
Sweet potato flour							
Sweet potato flour + wheat flour	Sweet potato flour 50 or 60% (cream fleshed or orange fleshed) + Refined wheat flour 27% (65:35; 69:31) + fiber sources (oat, wheat and rice bran) (10 or 20%) + 3% gelatinized cassava	Peeled SP; Soaked in acetic acid 1 h to prevent discoloration of flour; Extruded; dried at 50 °C – 18 h	10.44–14.88%	TA (2 mm/s; trigger force 5 g) = 0.590–1.246 N	/	/	Krishnan et al. 2012
	Sweet potato flour + Wheat flour (5:95; 10:90; 15:85; 20:80; 40:60) + salt (1% in water of hydration)	Peeled SP; Soaked 30min in 0.2% sodium metabisulfite before milling; Laminated; Fresh pasta	1.5–5.9%	TA (1mm/s; deformation of 80% of the initial thickness) 152.6–242.3 N	/	59 consumers (18–55 y) 6.1–7.7/9.0	Saleh, Lee, and Obeidat 2018
	Blanched sweet potato flour + Wheat flour (5:95; 10:90; 15:85) + salt (1% in water of hydration)	Peeled SP; Potato blanched at 90 °C during 2 min; Soaked 30 min in 0.2% sodium metabisulfite before milling; Laminated; Fresh pasta	1.6–2.3%	187.5–225.9 N	/	7.3–7.7/9.0	
	Purple Sweet potato powder + Wheat flour (2.5:97.5; 5:95; 7.5:92.5; 10:90) + 3g salt + 3 g olive oil	Heat treatment for potato powder; Extruded; Fresh pasta	10–17%	TA (200 g load cell. 70% of the original thickness; 0.5 mm/s) 0.58–0.68 N	Raw = L* = 41.06–60.25 a* = 9.62–22.37 b* = −0.71–0.67 Cooked = L* = 41.06–60.25 a* = 9.62–22.37 b* = −0.71–0.67	No information 4–6/9	Santiago et al. 2016
Sweet potato flour + other flour	Sweet potato flour + Pre gelatinized rice flour + (10:90) + 10% liquid egg albumen	Extruded; dried 50 °C during 14 h to reach 12% of moisture	10.9%	TA (No information) = 224 N	Raw = L* = 32.2 a* = 5.3 b* = 17.1	/	Marengo et al. 2018
	Sweet potato flour + Pre gelatinized rice flour + soybean flour (10:70:20) + 10% liquid egg albumen		10.6%	226 N	Raw = L* = 37.3 a* = 5.1 b* = 20.1	/	
	Orange fleshed sweet potato flour (<250 µm) + white corn flour (20:80; 30:70; 50:50)	Extrusion cooking (twin screw; T° = 60, 70, 80, 80, 80 for zones 1, 2, 3, 4 and 5; screw speed = 80 rpm); Dried at ambient T° overnight	4.36–12.50%	TA (load cell at 200 N; rate of 30 mm/min at 50% compression probe) 8.7–22.1 N	/	/	Baah, Duodu, and Emmambux 2022

CMC: carboxyl methyl cellulose; Extruded: low temperature extrusion; SP: sweet potato; TA: texture analyze; W: white; Y: yellow.

fleshed sweet potato flours increases b* value of pasta (Tables 2–4). For instance, Rizzello et al. (2017) showed 50% of b* value increase with 30% faba bean addition in DWS pasta compared to 100% DWS pasta. However, pasta made from purple fleshed sweet potato showed a decrease of b* value due to the RM color itself (Santiago et al. 2016).

Texture, color, and taste have an impact on pasta consumer's acceptability. Changes caused by the used of C-GF flours in pasta lead to a decrease of the consumer's acceptance (Tables 2–4). Hager et al. (2013) reported the presence of "hay-like" notes in 100% teff pasta that can explain the 30% reduction of the acceptance score compared to 100% DWS pasta. An unpleasant taste was also found by Santos et al. (2015) in pasta made with 35% amaranth flour. Education of consumers to these new tastes and texture can be questioned. Indeed, Laleg et al. (2017) reported that regular consumers of whole wheat pasta gave higher marks to 70 and 100% faba bean based pasta than consumers of classic DWS pasta. Although the marks obtained are lower than those attributed to 100% DWS classical pasta, they are identical to those of whole wheat pasta. And yet, some C-GF flours did not trigger a significant decrease of acceptance up to a threshold, e.g., 10, 20, and 30% for pigeon pea, orange fleshed sweet potato, and cowpea, respectively (Bergman and Weber 1994; Torres et al. 2006; Saleh, Lee, and Obeidat 2018). These C-GF flours can thus be depicted as more neutral on a sensorial point of view when mixed with DWS in pasta.

Impact of the replacement of common GF flours (corn and rice) by C-GF flours

C-GF flours can also be added to GF pasta traditionally made from corn or rice. Extrusion cooking and sheeting are used each in 25% of the studies in case of addition of C-GF flours in GF pasta, which is higher than for partial or total replacement of DWS by C-GF flours in pasta (10 and 20% for extrusion cooking and sheeting, respectively). In extrusion cooking process, especially for GF pasta, the protein is denatured; starch is gelatinized and retrograded for structure formation. The structure should allow water absorption during cooking without structural collapse, leading to lower CL as demonstrated by Marti, Seetharaman, and Pagani (2010). On the other hand, in sheeting process, the dough goes through two rotating cylinders. Mechanical energy used during this step is different (i.e., shearing stress, whereas elongational stress), which results in different pasta structure. Indeed, sheeted wheat pasta have a more compact and continuous protein network than extruded pasta (reviewed in Petitot, Abecassis, and Micard 2009).

The diversity of C-GF flours and the variety of processes used in the production of GF pasta affect their culinary quality. Some C-GF flour additions to GF pasta decrease CL contrary to what is observed in the case of an addition to DWS pasta (see section above). Marengo et al. (2015) reported a 25% decrease in CL with 15% of sorghum flour addition in rice extruded pasta especially due to the ability of sorghum proteins (i.e., mainly kafirin) to form a structured protein network that encapsulates starch granules. Suo et al. (2022) also found a 44% decrease in CL by adding 75% chickpea flour in rice and corn extruded pasta. The higher protein content of chickpea flour compared to corn or rice flours could have decreased the available water for starch swelling due to the increase in water-protein interactions. This can limit the amylose leaching in water (Padalino et al. 2015). However, the addition of faba bean or pigeon pea leads to an increase in CL. Gimenez et al. (2016) reported a 30% CL increase with 30% addition of faba bean flour in corn pasta made by extrusion-cooking. The same increase is observed by Rafiq, Sharma, and Singh (2017) with between 10 and 30% of pigeon pea flour addition in brown rice pasta made by extrusion cooking. Addition of tubers as sweet potato in GF pasta can also increase CL. Baah, Duodu, and Emmambux (2022) reported twice CL with addition of 30% of sweet potato in corn pasta compared to 100% corn pasta made by extrusion-cooking. Bouasla, Wójtowicz, and Zidoune (2017) and Baah, Duodu, and Emmambux (2022) suggest that a continuous structure is important for good quality pasta during extrusion cooking. The discontinuous structure observed when orange fleshed sweet potato is composited with corn flour probably occurs when fibrous material or incompatible ingredients are used (Baah, Duodu, and Emmambux 2022). A 45% decrease in pasta firmness is also reported with 30% of sweet potato addition in corn pasta (Baah, Duodu, and Emmambux 2022). The same decrease of firmness is observed by Suo et al. (2022) in case of 25% chickpea addition in corn and rice extruded pasta.

Impact of total replacement of DWS or common (corn and/or rice) GF flours by C-GF flours

Some pasta are also made from 100% C-GF flours. These pastas are 90% made with LT extrusion process against 10% by sheeting. LT drying is used more than 90% of the time. These pasta are GF which leads to a decrease of culinary quality compared to traditional DWS pasta as observed in case of a partial replacement of DWS by C-GF flours. Studies have yet to be done for 100% bambara groundnut, cowpea, pigeon pea, or sweet potato pasta. Pasta made from 100% C-GF cereal flour always contains others functional ingredients in formulation (Table 3). On the contrary, 100% C-GF legume or tuber pasta can be made without functional ingredients (Tables 2 and 4). Rachman et al. (2019), Garcia-Valle et al. (2021a) and Rosa-Sibakov et al. (2016) reported 6, 2, and 0.5 time fold increase of CL for 100% cassava, chickpea or faba bean based pasta, compared to their DWS control pasta, respectively. Hardness is also impacted, with a 30% decrease in case of 100% chickpea pasta compared to DWS control pasta (Garcia-Valle et al. 2021a). However, Rosa-Sibakov et al. (2016) observed a 50% increase in hardness with 100% faba bean pasta compared to DWS control. This difference between C-GF legumes can be explained by a fiber content twice as high in the chickpea flour compared to faba bean flour used in these studies, which disrupt the protein matrix and lead to a decrease in firmness. In comparison with traditional GF pasta (corn and/or rice pasta), 100% C-GF legume-based pasta has lower CL. For instance, 100% chickpea or faba bean have a 30 and 20% decrease in CL compared to traditional GF pasta, respectively (Laleg, Cassan, Barron, et al. 2016; Suo et al. 2022). A decrease of 45 and 60% of the hardness for 100% chickpea or faba bean pasta is also reported by Suo et al. (2022) and Laleg, Cassan, Barron, et al. (2016) in comparison to traditional GF pasta.

Impact of the process and pretreatments of flours

As for common GF pasta (corn and/or rice) process, some authors use processes, such as sheeting and extrusion-cooking to facilitate the C-GF flour pasta manufacturing (see paragraph above). A 30–100% increase in CL is observed in case of C-GF flours addition to traditional GF pasta (corn et/or rice) made by extrusion-cooking (Baah, Duodu, and Emmambux 2022; Gimenez et al. 2016; Rafiq, Sharma, and Singh 2017), whereas a 25–44% decrease in CL is reported with LT extrusion (Marengo et al. 2015; Suo et al. 2022). These results go against those of Marti, Seetharaman, and Pagani (2010), who found a decrease in CL when comparing the use of cooking-extrusion and LT extrusion processes on 100% rice pasta. This study being the single one to compare the two extrusion processes on a single formulation, it remains difficult to link the culinary properties to the use of a particular process considering the variability between all the studies in terms of nature and levels of RM used in formulation.

HT and VHT drying often used in DWS pasta are also used to improve culinary quality of pasta made with C-GF flours. Laleg et al. (2017) reported in 100% faba bean pasta, a CL decrease of more than 50% in case of HT drying instead of LT. HT and VHT induce disulfide bond formation in case of partial substitution of wheat by faba bean flour and thus lead to a stronger protein network which can better entraps starch granules and thus decrease CL (Laleg et al. 2017). However, the use of HT and VHT increases Maillard reaction and increases pasta "browning" which decreases pasta nutritional quality and overall acceptability (Anese et al. 1999).

Pretreatments as partial starch pre-gelatinization (in situ by flour steam treatment or by pregelatinized starch addition) affect its native physico-chemical properties leading to new pasta properties (Marti and Pagani 2013). They are classically used to improve the culinary and textural properties after cooking of rice pasta (Marti, Caramanico, et al. 2013). Marti, Caramanico, et al. (2013) found that the addition of severe parboiled rice and pregelatinized rice flour (50:50) led to the higher increase in pasta quality with a decrease in CL and an increase in water absorption. The effect is due to amylose retrogradation leading to a crystalline structure of starch post-extrusion and during drying which forms a network surrounding native starch granules (from non-pre-gelatinized flour). Some authors, such as Fiorda, Soares, et al. (2013), Palavecino et al. (2017), Martín-Esparza et al. (2018), or Marengo et al. (2015) are using pre-gelatinized flour in their pasta made from C-GF flours. However, no CL changes are observed in case of addition of 10% of pre-gelatinized tiger nut flour in chickpea-tiger nut (50:50) pasta (Martín-Esparza et al. 2018).

Finally, flour fermentation used to reduce anti-nutritional factors and thus improve the nutritional quality (increase of protein digestibility and decrease of GI) of pasta can impact their culinary quality (CL) as demonstrated by Lorusso et al. (2017) on quinoa/wheat (20:80) pasta with the use of fermented quinoa flour. Applied on C-GF, such as cassava, fermentation increases the CL of pasta by 60% compared with unfermented pasta (Odey and Lee 2019). Fermentation of cassava or faba bean increase by 30 and 160% a* value of pasta compared to unfermented flour, respectively due to Maillard reaction (Odey and Lee 2019; Rosa-Sibakov et al. 2016).

Impact of the addition of functional ingredients

As on traditional GF pasta (Gao et al. 2017), proteins, transglutaminase (TGase), emulsifiers, starch, and other hydrocolloids, can be added as functional ingredients to the formulation based on C-GF flours in order to preserve or limit textural, culinary and organoleptic property changes in pasta. They are used in up to 50% of pasta made from 100% C-GF flours and only 15% of pasta containing a mix of wheat and C-GF flours because culinary properties are more preserved with the presence of gluten.

Sodium caseinate, whey or soy protein, eggs (fresh or powder) form a gel after protein denaturation increasing the strength of the protein network by formation of disulfide bonds. They are often used as protein additives in traditional GF pasta (Phongthai et al. 2017). The use of these additives in C-GF pasta results in a decrease in CL and an increase in pasta firmness compared to additive free C-GF pasta. For instance, the addition of 15% of egg white powder in 100% amaranth or banana-cassava pasta decreases their CL by 13 and 82%, and increases their firmness by 4 and 6 times, respectively (Schoenlechner et al. 2010; Rachman et al. 2020). The effect on CL is in accordance with results obtained by Marti, Barbiroli, et al. (2013) on common GF pasta (rice), who reported a 36% decrease in CL with 15% egg albumen. However, the effect on firmness remained insignificant on GF rice pasta. According to Rachman et al. (2020), soy protein was less efficient than egg protein for the same amount of protein addition, with only a 65% decrease in CL and a 23% increase in firmness in banana-cassava pasta. However, despite an improve in textural and culinary properties, Manoj Kumar et al. (2019) reported a 40% increase of a* value with 20% of sodium caseinate addition in 100% millet pasta, may be due to an increase in the Maillard reaction with the increase of available lysine provided by caseinate.

TGase, forming covalent linkages between glutamine and lysine residues can also be added as functional ingredient in GF pasta to strength the protein network and improve pasta quality (Folk and Finlayson 1977). Concerning C-GF pasta, Rosa-Sibakov et al. (2016) and Manoj Kumar et al. (2019) added 20 nkat of TGase/g flour d.m. and 0.5–1.5% of TGase (w/w; 100 U activity) in 100% faba bean and 100% millet pasta, respectively. There is no significant decrease of CL in faba bean pasta (Rosa-Sibakov et al. 2016) and a 17% increase of CL is reported in the case of millet pasta (Manoj Kumar et al. 2019) with TGase addition. This low impact on CL is also reported in common GF pasta (corn) with only 6% decrease of CL with 0.5% TGase addition (Yalcin and Basman 2008). Manoj Kumar et al. (2019) have shown no impact on millet pasta firmness despite Rosa-Sibakov et al. (2016) demonstrated an increase of faba bean pasta firmness by 1.5 which is in accordance with the 1.3 firmness increase reported by Yalcin and Basman (2008) for 0.5% TGase in corn GF pasta. The addition of TGase increases yellowness in both faba bean and millet pasta. Even if pasta properties are not totally improved by TGase, Manoj Kumar et al. (2019) reported an increase in overall acceptability in millet pasta. Protein or TGase addition both lead to covalent bond formations in pasta. However, TGase lower improves culinary property than a protein addition, such as egg powder. The lack of improvement in case of TGase addition especially in millet pasta can be due to the low content of protein and thus lysine residue in millet flour, which limits effectiveness of TGase.

Emulsifiers, i.e., distilled mono and di-glycerides and diacetyl tartaric acid, by forming amylose-lipid complexes decreasing starch retrogradation, reduce the risk of brittleness and improve the texture of GF pasta as reviewed by Marti and Pagani (2013). These additives used in C-GF pasta formulations, also improve their textural and culinary properties. Schoenlechner et al. (2010) reported a 12% decrease of CL and a 165% increase in firmness with the addition of 1.2% distilled mono glycerides in 100% amaranth pasta. Effect of emulsifier highly depends of its nature as reported Lai (2002) with a 15 or 50% decrease of CL with the use of 1% commercial emulsifier (KM 300) or distilled glyceryl monostearate in common GF pasta (rice), respectively.

Hydrocolloids, such as xanthan and guar gums or carboxyl methyl cellulose used in classical GF pasta are also added in C-GF pasta formulation. Even if their mechanism of action is not well described in the literature, they would act by stabilization of the pasta structure due to their viscous and gelling properties strengthening the protein network and constraining therefore starch granules therefore improving rheological properties (reviewed by Padalino, Conte, and Del Nobile 2016). Indeed, Yadav et al. (2012) reported a slight decrease of 4% of CL and an 8% increase of firmness between the addition of 2.5 and 3.5% of carboxyl methyl cellulose in millet based-pasta. However, this effect remains low in comparison to the 70% decrease of CL obtained on common GF pasta with the use of 0.35% of xanthan gum or guar gum (Kaur et al. 2015). Hydrocolloid additions have a lower impact on C-GF flour pasta culinary properties than the addition of proteins or emulsifiers but present the advantage to not significantly affect pasta color in contrary to protein additions (Motta Romero et al. 2017). Gull et al. (2015) reported therefore a 15% increase in the overall acceptability score of millet pasta with the addition of 1.5% of carboxyl methyl cellulose.

Digestibility of pasta made from C-GF cereal, legume, and tuber flours

Overview of parameters that define starch and protein digestibility of pasta

Some authors attempt to assess the nutritional quality of pasta, in particular by measuring the digestive fate of its protein and starch content. For this purpose, advanced *in vivo* methods on rats and/or humans allow to obtain digestibility and bioavailability parameters. *In vitro* methods which are less costly and time consuming than *in vivo* methods, have been also used to approach these parameters.

More than 75% of the studies have based their protein digestibility and bioavailability values on *in vitro* measurements. Protein digestibility is calculated thanks to nitrogen or free amino groups (NH_2) content available after enzyme *in vitro* digestion. Several *in vitro* methods are used which make comparison between studies difficult. Some studies make pepsin and pancreatin digestion, such as Pasini et al. (2001) and Akeson and Stahmann (1964) methods which both use different incubation times (Appendix A). Moreover, other studies use the Hsu et al. (1977) and Bodwell et al. (1980) methods including trypsin, chymotrypsin, and peptidase enzyme for protein digestion. There is now a standardized static *in vitro* method COST INFOGEST (Minekus et al. 2014; Brodkorb et al. 2019) which has not been used in the studies on C-GF pasta presented in this review but which would allow future *in vitro* digestion results to be harmonized and comparable. To measure protein bioavailability, *in vivo* studies on rats have been assessed. Net protein utilization (NPU) and biological value (BV) are *in vivo* indicators of protein digestibility and are calculated using the following Equations (2)–(4) (Proll et al. 1998):

$$NPU(\%) = \frac{NI - (FN + UN) + EBFN + EUN}{NI} \times 100 \qquad (2)$$

$$CFD(\%) = \frac{NI - (FN - EBFN)}{NI} \times 100 \qquad (3)$$

$$BV(\%) = \frac{NPU}{CFD} \times 100 \qquad (4)$$

With: CFD = Corrected Fecal Digestibility; EBFN = Endogenous and Bacterial Fecal; EUN = Endogenous Urinary Nitrogen; Nitrogen FN = Fecal Nitrogen Intake; NI = Nitrogen Intake; UN = Urinary Nitrogen.

GI evaluates the postprandial glycemia after the ingestion by human subjects of carbohydrate-containing food. Foods can be ranked into three categories, i.e., low (GI ≤ 55), moderate (GI between 55 and 69), and high (GI ≥ 70) GI (reviewed in Atkinson et al. 2021). A predicted Glycemic Index (pGI) can be determined based on the *in vitro* starch hydrolysis index (starch hydrolyze curve of product during 2 or 3 h compared to a glucose solution) (Goni, Garcia-Alonso, and Saura-Calixto 1997). Others methods differentiate the digestibility of starch after 20 min and between 20 and 120 min of pancreatin, invertase, and amyloglucosidase incubation and the residual starch (Englyst, Kingman, and

Cummings 1992) giving therefore an amount of Rapidly Digestible Starch (RDS), Slowly Digested Starch (SDS) and Resistant starch (RS) in sample. Englyst and Hudson (1996) also expressed the results in Rapidly Available Glucose (RAG) and Slowly Available Glucose (SAG), which take into account glucose released from sample free sugar in contrary to RDS and SDS. Starch digestibility indicators RAG and RDS are highly correlated with *in vivo* determination of GI (Englyst and Hudson 1996).

Pasta are interestingly low GI food due to the presence of strong protein matrix that entraps starch granules, thus limiting the enzymatic hydrolysis (Colonna et al. 1989; Granfeldt and Bjorck 1990). *In vitro* protein digestibility generally ranges from 80 to 90% for DWS pasta independently of the method used: Hsu et al. (1977) or Pasini et al. (2001). To keep this nutritional quality, the addition of C-GF flour in DWS pasta should not increase GI, nor decrease protein digestibility (*in vivo* and/or *in vitro*). The use of a particular process to improve pasta textural, culinary, and organoleptic properties may also have an impact on digestibility as it may modify the fine structure of the food (Laleg, Greffeuille, et al. 2019).

Impact of the addition of C-GF flour

The comparison of the digestibility of pasta made from C-GF flours is challenging due to the high variability in methods of formulations, processes, and digestibility. In this review, we only focused on protein and starch digestibility. Indeed, lipid digestibility and antioxidant bioavailability are scarcely reported in studies in relation to their low contents in these matrices. In this review, we chose to represent the difference in digestibility of pasta made from C-GF flours compared to the wheat pasta (control) of each study (Figures 1 and 2). Only studies comparing their results to a wheat control are therefore represented (around 80% of studies). All studies about protein and starch digestibility are resumed in tables A and B in Appendix, respectively. Figure 1 represents only the *in vitro* protein digestibility and Figure 2 includes several indicators of carbohydrate digestibility, such as *in vitro* and *in vivo* GI, RDS, and RAG.

Even if addition of C-GF flours leads to a weaker protein network compared to wheat pasta (see previous section), more than the half of formulations found pasta protein digestibility to remain the same or even decrease compared to wheat pasta. It is the case of formulations with 80–100% of millet in pasta, 10 to 30% of cowpea, and those with <13.5% of chickpea flour in pasta (Figure 1). The higher fiber amounts and anti-nutrient factors in C-GF flours compared to wheat semolina (Tables 1A and 1B) can limit the protease access to substrate and its activity (see previous section) (Bergman, Gualberto, and Weber 1996; Samtiya, Aluko, and Dhewa 2020). The 4 to 50% decrease in protein digestibility of pasta containing 80 and 100% millet compared to wheat control (Rathi, Kawatra, and Sehgal 2004; Cordelino et al. 2019) can also be explained by the higher millet proportion (>80%) in pasta compared to the proportion of other C-GF flour (<50%) in formulations presented in Figure 1. The high decrease of 52% of protein digestibility obtained with 100% millet pasta (Cordelino et al. 2019) contrasts with

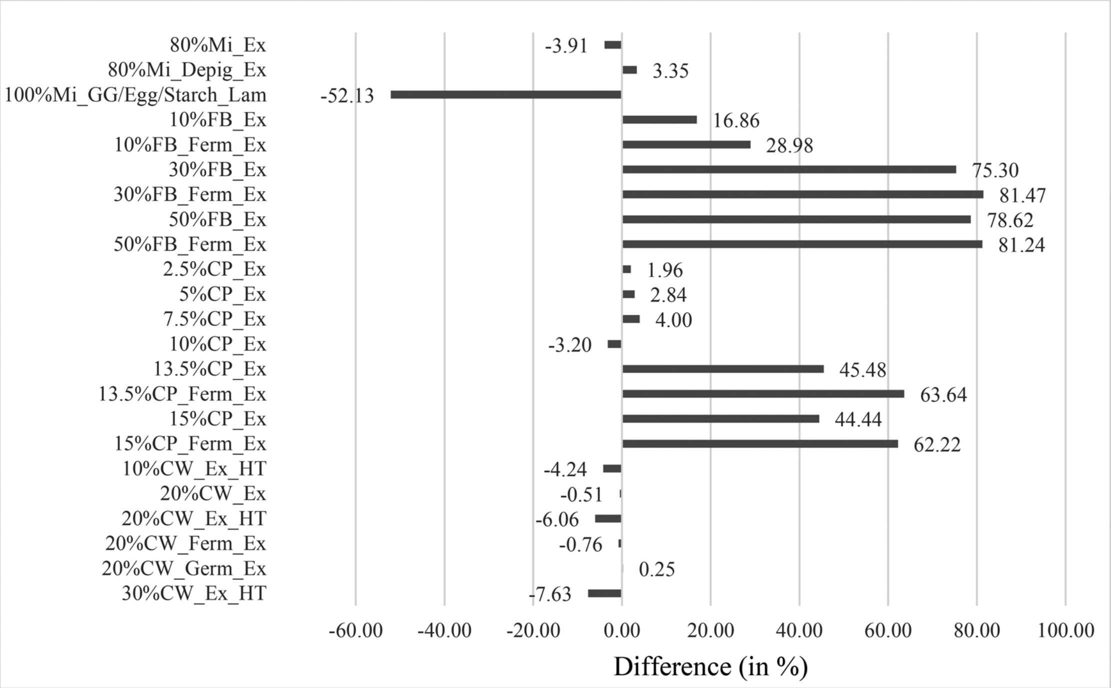

Figure 1. Difference (in %) of protein digestibility between climate-smart gluten-free flour-based pasta and their respective wheat control in each study. Protein digestibility is obtained by *in vitro* methods. Each line represents one pasta formulation. Percentage corresponds to the fraction of climate-smart gluten-free flours in pasta. Mi: millet; FB: faba bean; CP: chickpea; CW: cowpea; Ex: extruded pasta (low temperature); Lam: laminated; Depig: depigmented flour; GG: guar gum; Ferm: fermented; Germ: germinated; HT: high temperature drying; If HT is not indicated drying took place at low temperature.

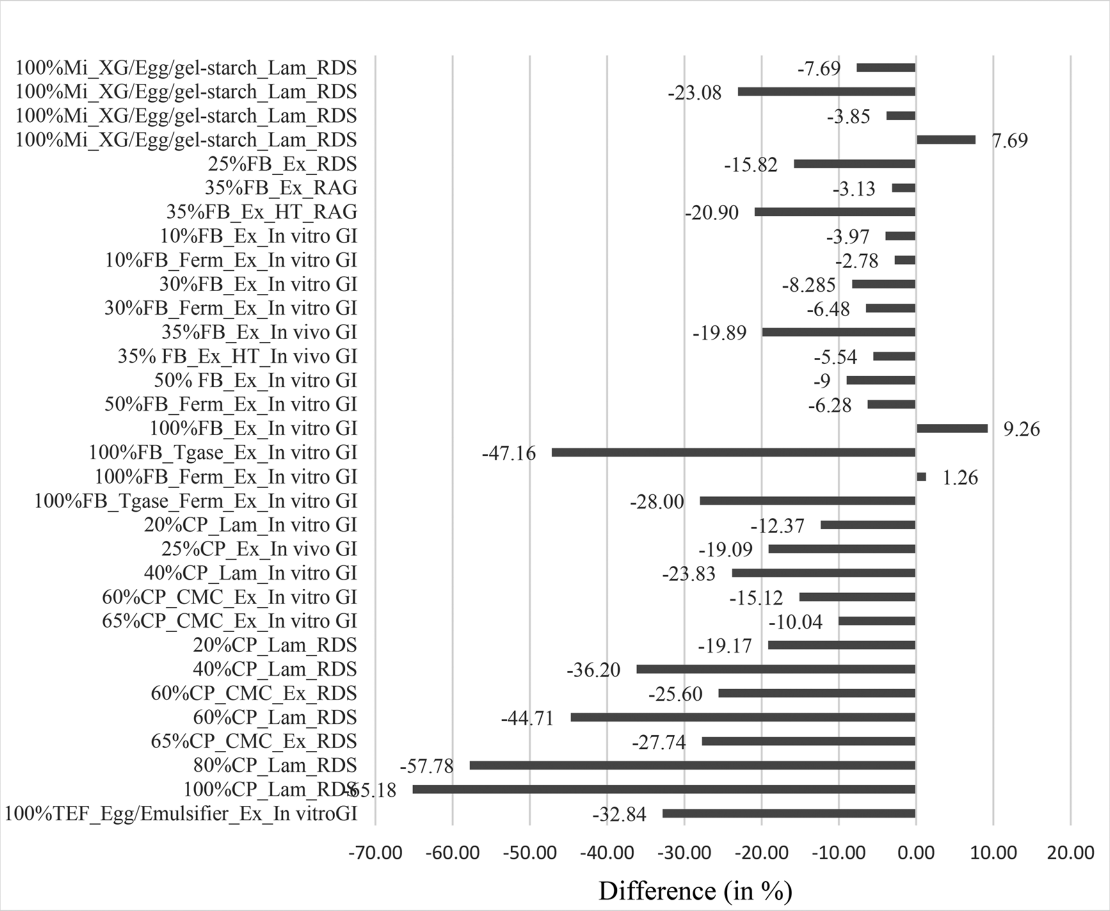

Figure 2. Difference (in %) of carbohydrate digestibility between climate-smart gluten-free flour-based pasta and their respective wheat control in each study. Carbohydrate digestibility was obtained by *in vivo* (GI) and *in vitro* (pGI, RDS, RAG) methods. Each line represents one formulation except 10, 30, and 50%FB_Ex_*In vitro* GI (mean of the same formulation in two different studies). Percentage corresponds to the fraction of climate-smart gluten-free flour in pasta. Mi: millet; FB: faba bean; CP: chickpea; TEF: teff; Ex: extruded pasta (low temperature); Lam: laminated; XG: xanthan gum; Tgase: transglutaminase; CMC: carboxyl methyl cellulose; gel-starch: pre-gelatinized starch; Ferm: fermented; Germ: germinated; HT: high temperature drying; If HT is not indicated drying took place at low temperature.

the 3% decrease only reported by Rathi, Kawatra, and Sehgal (2004) for 80% millet pasta. The use of laminated process on 100% millet pasta instead of extrusion by Cordelino et al. (2019) probably gave a higher compact and continuous protein network as reviewed in Petitot, Abecassis, and Micard (2009), making it more resistant to protease attack. Gulati et al. (2017) also showed that pasta process, such as heating with or without excess (i.e., cooking step) of water has a negative impact on millet protein digestibility: hydrophobic interactions occur and may expose tryptophan residues which decrease their availabilities and thus decrease the protein digestibility of pasta. A decrease in protein digestibility from 4.2 to 7.3% in case of 10 to 30% cowpea-based pasta compared to wheat pasta is reported by Bergman, Gualberto, and Weber (1996). The higher content of reducing sugar in cowpea flour compared to wheat flour favors Maillard reaction and thus decreases the availability of lysine. HT drying used for 20 and 30% cowpea formulation induces a fortification of the protein network by protein cross-linking which can affect negatively the protein digestibility. In the case of chickpea addition, a threshold effect seems to occur on protein digestibility from 13.5% of chickpea added (Figure 1). Below 13.5% of chickpea addition, the protein digestibility remains the same as wheat (El-Sohaimy et al. 2020). From 13.5 to 15% chickpea addition in wheat pasta leads to an increase of around 45% in protein digestibility compared to wheat pasta (Schettino, Pontonio, and Rizzello 2019; De Pasquale et al. 2021). However, the difference in digestibility compared to wheat control observed between 10 and 13.5% of chickpea in pasta vary from −3.2% to more than 45% which may not only due to chickpea content but also probably from the difference between studies, notably the use of two different *in vitro* digestibility methods. Moreover, the addition of 10–50% of faba bean flour in DWS pasta increases by 17–79% the protein digestibility compared to wheat pasta (Figure 1). Laleg et al. (2017) observed a linear increase of weakly-linked protein and a decrease of disulfide bond with the addition of faba bean in DWS pasta. This could facilitate the attack by proteases and therefore increase protein digestibility. Concerning *in vivo* models, the increase of protein digestibility is not found any more in the rat with the addition of 35% of faba bean flour in DWS pasta compared to DWS pasta, may be due to higher fiber and ANF content (Laleg, Salles, et al. 2019)

(Appendix A). Torres et al. (2006) reported a 6% increase of *in vivo* true digestibility in rats and 1.7 times higher protein efficiency ratio with the addition of 10% of pigeon pea flour in DWS pasta compared to 100% DWS pasta (Appendix A).

The weakness of the protein network induced by the total or partial replacement of DWS by C-GF flours may theoretically lead to an increase of the starch hydrolysis and therefore the GI of pasta. However, the addition of C-GF flours in pasta seems to decrease or does not have any effect on starch hydrolysis and GI (Figure 2). Only laminated 100% millet pasta and extruded 100% faba bean pasta led to the increase of more than 5% of the RDS and *in vitro* GI, respectively (Rosa-Sibakov et al. 2016; Cordelino et al. 2019). Difference of carbohydrate RDS occurred in the four laminated 100% millet pasta which could be due to the use of different varieties of millet (Figure 2, Cordelino et al. 2019) and especially their difference in amylose composition which could have impacted their carbohydrate digestibility (Cordelino et al. 2019). Indeed, high amylose:amylopectin ratio, leads to higher retrogradation after gelatinization and therefore to the formation of crystal structure more difficult to access for amylases (reviewed by Petitot, Abecassis, and Micard 2009).

The increase in the proportion of C-GF flours in pasta decreases the RDS compared to wheat pasta (Figure 2). For instance, the addition of 20–100% of chickpea flour in wheat pasta leads to a linearly decrease in RDS compared to wheat pasta from 19 to 65% (Figure 2). This is accompanied by a decrease in SDS and an increase in RS compared to wheat pasta (Appendix B). The addition of 10–50% of faba bean in wheat pasta leads to a decrease from 4 to 9% of *in vitro* GI compared to wheat control pasta (Figure 2). Chickpea flour addition seems to have a higher impact on carbohydrate digestibility than faba bean addition (Figure 2). The decrease in carbohydrate digestibility of C-GF legume based pasta compared to wheat pasta can be related to the higher RS content of legume flour compared to wheat flour (Yadav, Sharma, and Yadav 2010), and to a higher protein amounts which can form a thicker protein network that encapsulates starch granules and therefore create a more significant physical barrier to digestible enzymes (Laleg, Barron, Sante-Lhoutellier, et al. 2016; Rosa-Sibakov et al. 2016) which can counteract the weakening of the gluten network. Moreover, the higher presence of ANF as polyphenols and phytic acids in C-GF flours can also have an impact on starch hydrolysis with inhibition of the α-amylase activity (Thompson and Yoon 1984). These ANF are also responsible for a decrease in the attack of proteins by digestive enzymes, which does not allow amylase to easily reach starch granules entrapped in the protein network.

Impact of functional ingredients and process

Several functional ingredients used for pasta formulation when DWS is totally or partially replaced by C-GF flours decrease starch digestibility. It is the case of the addition of soluble fibers due to their gel forming ability. Indeed, the addition of 1.5% of gums, such as guar and xanthan leads to 15 and 20% decrease in RDS fraction with a complementary increase of RS in sweet potato pasta (Menon, Padmaja, and Sajeev 2014) (Appendix B). There is no additional decrease in starch digestibility with the combination of xanthan and 10–20% apple fibers compared to xanthan alone (Menon, Padmaja, and Sajeev 2014).

The addition of TGase (20 nkat/g flour d.b.) in a 100% faba bean pasta strengthens its protein network surrounding starch therefore limiting amylase hydrolysis. This induces a 50% decrease of *in vitro* GI compared to formulation without TGase (Rosa-Sibakov et al. 2016).

Flour pretreatments can also have an impact on protein and carbohydrate digestibility. Flour fermentation or depigmentation by soaking increases protein digestibility. In chickpea pasta the *in vitro* protein digestibility increases by 12% when using 15% of fermented (8 h) instead of non-fermented chickpea flour in pasta (De Pasquale et al. 2021). Increase of protein digestibility is also reported for faba bean-based pasta (Figure 1) with the addition of 10, 30, or 50% of 24 h fermented instead of non-fermented faba bean flour in pasta (Rizzello et al. 2017). The use of depigmented (by soaking) instead of native pearl millet flour induces an increase of 7.5% in protein digestibility (Rathi, Kawatra, and Sehgal 2004). Fermentation and soaking leach out the ANF in water which can explain the increase in protein digestibility (Rathi, Kawatra, and Sehgal 2004). Moreover, fermentation induces a decrease in pH which leads to phytase activation. Phytic acid is therefore degraded which increases protein digestibility (reviewed in Gobbetti et al. 2019). In terms of starch digestibility, flour pretreatments have different impacts. The decrease of ANF, such as amylase inhibitors, phytic acid, and polyphenols, combined with the swelling of starch granules during soaking or fermentation process can lead to an increase in starch digestibility. The use of 10, 30, and 50% fermented faba bean instead of non-fermented faba bean in pasta leads to an increase of 12–16% in carbohydrate digestibility (Rizzello et al. 2017). On the other hand, the acidification caused by fermentation can move away salivary amylase from its optimal pH and thus decrease its efficiency (Angelis et al. 2009). The use of 10 min fermented faba bean flour in 100% faba bean pasta decreases the *in vitro* GI of 7% (Rosa-Sibakov et al. (2016). Schettino, Pontonio, and Rizzello (2019) also reported a 20% decrease in the hydrolyze index in case of the replacement of 13% chickpea flour by 8 h fermented one (Appendix B).

The other process that affects protein and starch digestibility is the HT drying. This process leads to the formation of disulfide bonds which make a stronger protein network that encapsulates starch granules therefore decreases the efficiency of digestive enzymes (Petitot and Micard 2010; Greffeuille et al. 2015). There is an 18% decrease of RAG on 35% faba bean-DWS pasta with the use of HT drying (Greffeuille et al. 2015).

Conclusion

C-GF cereals, legumes, and tubers can be incorporated into DWS pasta, traditional GF pasta (made from corn or rice), or even used alone, to enhance the nutritional profile of pasta. This beneficial effect is primarily attributed to the higher protein, fiber, vitamin, and mineral contents of C-GF flours compared to wheat, corn, or rice. Moreover, the addition of C-GF flours in DWS pasta does not impact or even increases its protein digestibility nor decreases its carbohydrate digestibility compared to wheat control pasta. However, biochemical changes occur, that have an impact on the culinary and techno-functional properties of pasta. The partial or total replacement of DWS by C-GF flours in pasta highly increases their CL, decreases their firmness in most cases, and modifies their color with a decrease in lightness. These changes decrease the overall acceptability of C-GF flour-based pasta compared to classical ones. On the contrary, the addition of C-GF flour in traditional GF pasta made from corn and/or rice can improve their culinary qualities by decreasing CL which makes them interesting flours for the preparation of GF pasta. Special process (extrusion-cooking, HT drying, flour pretreatments) and/or the addition of functional ingredients can be used to improve C-GF flour-based pasta quality, which can also affect (negatively or positively) the nutritional quality of pasta. Protein and hydrocolloid addition are useful additives to keep or even improve the nutritional qualities of pasta while improving their culinary quality. The diversity of methods used to characterize the culinary properties of pasta makes comparison between studies and RM difficult. However, in general, C-GF legume flours have a higher nutritional quality than C-GF cereals and tubers (higher protein, fiber, and micronutrient contents; higher CS and PDCAAS). Moreover, pasta made with 100% C-GF legume flour can be processed without any functional additives. Finally, pasta partially or totally made from C-GF legumes have higher protein digestibility while keeping low GI. Pasta made with faba bean and chickpea flours are the most studied, but it would be interesting to broaden the view, studying for instance bambara groundnut or pigeon pea pasta due to their potentially high nutritional quality. Furthermore, while introducing new RM in pasta, the study of their potential allergenicity especially in western populations is a high priority in the near future.

Disclosure statement

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Appendices

Appendix A. Resume of protein digestibility of climate-smart gluten-free (C-GF) flour-based pasta

Flours	Formulation	Process	Conditions	Indicators	References
Sorghum	Brown/White sorghum flour + XG (2.5%) + egg albumen (11%) + egg powder (5.7%) + pre-gelatinized starch (1%)	Dehulled sorghum; Extruded; dried first at 40 °C − 30 min and then 45 °C − 17 h, RH = 75%	*In vitro* method = OPA reagent and serine [Nielsen 2001 method]	PD = 66–86%	Palavecino et al. 2019
Millet	41–46 g Millet flour + 16 g potato starch + 0.2 g salt + 0.8 g GG + 28 g liquid eggs	Decorticated millet; Laminated	*In vitro* method = pepsin (pepsin:protein ratio, 1:30) 1 h 37 °C + pancreatin (pancreatin:protein ratio, 1:21) 1 h 37 °C [Pasini et al. 2001 method]	PD = 41–50%	Cordelino et al. 2019
	Pearl millet flour + Chickpea flour (80:20)	Extrusion; dried 40 °C–2 h	*In vitro* method = pepsin [Mertz 1983 method]	PD = 68.8%	Rathi, Kawatra, and Sehgal 2004
		Depigmented millet (soaked 18 h 30–35 °C); Extrusion; dried 40 °C − 2 h		PD = 74.0%	
Amaranth	Whole amaranth flour + Durum wheat flour (5:95; 15:85; 25:75; 30:70)	Extruded (49.5 °C; extrusion speed 20 rpm); dried 30–40 °C, RH = from 95 to 61%; 18 h	*In vitro* method = 1.6 mg trypsin, 3.1 mg chymotrypsin and 1.3 mg peptidase/mL; PD calculated from pH change [Hsu 1977 method]	PD = 84.2–86.2%	Rayas-Duarte, Mock, and Satterlee 1996
	Whole amaranth flour + Rice flour (25:75)	Extruded; dried 50 °C − 14 h	*In vitro* method = 1.6 mg trypsin, 3.1 mg chymotrypsin and 1.3 mg peptidase/mL; pH measure [Hsu 1977 method]	PD = 84.0%	Cabrera-Chávez et al. 2012
		Pre-treated flour in a two zone extrusion-cooker (2 min; 120 °C. single screw); pasta making in extruder; Dried at 50 °C − 14 h		PD = 82.9%	
Chickpea	Chickpea flour + DWS (2.5:97.5; 5:95; 7.5:92.5; 10:90)	Extruded (spaghetti)	*In vitro* method = pancreatic trypsin (15,310 U/mg protein), pancreatic chymotrypsin (48 U/mg solid), intestinal peptidase (115 U/g solid) 37 °C 10 min + bacterial protease (4.4 U/mg solid) 55 °C 9 min; pH measure [Bodwell 1980/Carbonaro et al., 1997 method]	PD = 89.0–95.6%	El-Sohaimy et al. 2020
	Black chickpea flour + WS (15:85)	Extruded; dried at 55 °C − 8 h	*In vitro* method = pepsin 3 h 37 °C + pancreatin 24 h 37 °C [Akeson 1964 modified method]	PD = 65%	De Pasquale et al. 2021
	Fermented chickpea flour + WS (15:85)	Fermentation in 30 °C tap water; Extruded 50 °C; dried at 55 °C − 8 h		PD = 73%	
	Chickpea flour + DWS (13.5:86.5)	No coarse fraction; Extrusion 45–50 °C; Dried at 55 °C, duration not know	*In vitro* method = pepsin 3 h 37 °C + pancreatin 24 h 37 °C [Akeson 1964/Rizzello et al., 2014 method]	PD = 65.6%	Schettino, Pontonio, and Rizzello 2019
	Fermented Chickpea flour + DWS (13.5:86.5)	No coarse fraction; Fermentation in 30 °C water; Extrusion 45–50 °C; Dried at 55 °C, duration not know		PD = 73.8%	
Faba bean	Faba bean flour	Dehusked faba bean; Extruded; HT drying : 90 °C to reach 12% moisture	*In vitro* method = 37 °C, pepsin (73.4 U/g of protein of pepsin) 30 min + pancreatin (10.4 USP/mL of pancreatin) 180 min [Pasini et al. 2001 modified method]	PH = 52% of proteins	Laleg et al. 2017
	Faba bean flour + DWS (35:65; 70:30)	Dehusked faba bean; Extruded; dried at 55 °C to reach 12% moisture		PH = 46% of proteins	
		Dehusked faba bean; Extruded; HT drying : 90 °C to reach 12% moisture		PH = 47% of proteins	
	Faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled faba bean; Extruded 45–50 °C; dried at 55 °C, duration not know	*In vitro* method = pepsin 37 °C 3 h + pancreatin 37 °C 24 h [Akeson 1964/Rizzello 2014 method]	PD = 49.2–75.2%	Rizzello et al. 2017
	Fermented faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled faba bean; Fermentation 30 °C during 24 h; Extruded 45–50 °C; dried at 55 °C, duration not know		PD = 54.3–76.3%	
	Faba bean + DWS (35:65)	Extrusion; dried at 55 °C, RH = 70–90%, 15 h	*In vivo* method = 10 rats per diets (1 month old male); 21d of diet	BV = 77.9% NPU = 76.4%	Laleg, Salles, et al. 2019
		Extrusion; HT drying : 90 °C, RH= 70–90%, 3 h		BV = 74.3% NPU = 72.3%	
	Faba bean flour + DWS (62:38)	Extruded; dried at 55 °C − 15 h	*In vivo* method = 27 old male rat; 6 weeks diet	BV = 42.6% NPU = 39.2%	Berrazaga et al. 2020
	Faba bean flour + DWS + Buckwheat flour (5:77:18) + lupin protein isolate 1.55% + NaCl 0.3%	Extruded	*In vitro* method = pepsin 37 °C 1 h + pancreatin 37 °C 1, 3, and 24 h; enzyme/substrate ratio at 1:50 (pepsin) and 1:10 (pancreatin)	PD = 1.6 (pepsin 1 h); 16.5; 23.6; 31.0% (pancreatin 1, 3, and 24 h)	Hoehnel et al. 2020
	Faba bean flour + Corn flour (30:70)	Dehulled faba bean; Extrusion cooking (single screw, 100 °C, 60 rpm); dried at 40 °C, RH = 40%, 16 h	*In vivo* method = 12 rats (25–35 d old rats); 10 d of diet	TPD = 80.8% BV = 69.0% PDCAAS = 49.9	Gimenez et al. 2016

(*Continued*)

Appendix A Table. Continued.

Flours	Formulation	Process	Conditions	Indicators	References
Cowpea	Cowpea flour + DWS (20:80)	Soaked 10 h in distilled water; Decorticated; Boiled and milled; Extruded; dried 40 °C, RH = 60%; dried until 10–12% of final moisture	*In vitro* method = trypsin (13,766 U/mg protein) + chymotrypsin + peptidase; pH measure [Hsu 1977/Dahlin and Lorenz, 1993 method]	PD = 78.5%	Nur Herken et al. 2006
	Cowpea flour (germinated or fermented) + DWS (20:80)	Soaked 10 h in distilled water; Decorticated Germination (30 °C, 24 h in oven) OR Fermentation (30 °C, 24 h in water); Extruded; dried 40 °C, RH = 60%, dried until 10–12% of final moisture		PD = 79.1% (germinated) and 78.3% (fermented)	
	Cowpea flour + Soft wheat flour (10:90; 20:80; 30:70)	Dehulled cowpea; Extruded; HT drying: 40 °C – 1 h + 80 °C – 2 h + 40 °C – 2 h	*In vitro* method = solution with trypsin (23,100 U/mL) + chymotrypsin (186 U/mL) + peptidase (0.052 U/mL); 10 mg nitrogen for 1 mL enzyme solution [AOAC 1990 method]	PD = 78.2–81.0%	Bergman, Gualberto, and Weber 1996
Pigeon pea	Pigeon pea flour + DWS + Brown rice flour (20:40:40)	Cooking extrusion (30, 40, 50, and 70 to 110 °C in the 4 sections, respectively, twin screw); dried 50–60 °C, duration not know	*In vitro* method = pepsin 37 °C 3 h + pancreatin 37 °C 24 h [Akeson 1964]	PD = 50.3–84.8%	Rafiq, Sharma, and Singh 2017
	Fermented pigeon pea flour + DWS (10:90)	Fermentation = 42 °C 48 h in distilled water; 15 min rested after hydration; Extruded (single screw); pre-dried at ambient temperature for 1 h and dried at 50 °C – 2 h	*In vivo* method = 6 week old rats (3 males 3 females); 14 d diet	TPD = 89.6%	Torres et al. 2006

BV: biological value; DWS: durum wheat semolina; d: day; Extruded: low temperature extrusion; HT: high temperature; GG: guar gum; NPU: net protein utilization; PD: protein digestibility; PH: protein hydrolysis; RH: relative humidity; TPD: true protein digestibility; WS: wheat semolina; XG: xanthan gum.

Appendix B. Resume of carbohydrates digestibility of climate-smart gluten-free flour-based pasta

Flours	Formulation	Process	Conditions	Indicators	References
Sorghum	Brown/White sorghum flour + XG (2.5%) + egg albumen (11%) + egg powder (5.7%) + pre-gelatinized starch (1%)	Dehulled sorghum; Extruded; dried first at 40 °C – 30 min and then 45 °C – 17 h, RH = 75%	*In vitro* method = Digestion = COST Infogest protocol [Minekus et al. 2014] GI = pepsin (115 U/mL) 30 min 37 °C + pancreatic alpha-amylase 37 °C (110 U/mL); aliquots during 180 min; maltose dosage [Goni 1997/Brennan 2004]	RDS = 33.3–38.4 g SDS = 16.0–19.4 g RS = 45.6–47.3 g pGI = 62–65	Palavecino et al. 2019
	Whole red or white sorghum flour + DWS (20:80; 30:70; 40:60)	10 min rested after hydration; Laminated; dried at room temperature (21/25 °C) during 30 h to reach <10% moisture	*In vitro* method = alpha amylase + pepsin 30 min at 37 °C + pancreatin/ amyloglucosidase; aliquot during 120 min; glucose dosage [Sopade and Gidley, 2009]	RDS = 10.7–15.2 g (red sorghum) and 16.2–20.2 g/100 g dry starch (white) SDS = 36.3–36.7 g (red) and 36.1–37.7 g/100 g dry starch (white)	Khan et al. 2014
Millet	41–46 g Millet flour + 16 g potato starch + 0.2 g salt + 0.8 g GG + 28 g liquid eggs	Decorticated millet; Laminated	*In vitro* method = pancreatin, invertase, amyloglucosidase; 37 °C aliquots during 120 min; glucose dosage [Englyst 1992/Annor et al., 2013]	RDS = 10–15 g/100 g pasta (w.b) SDS =10–15 g/100 g pasta (w.b)	Cordelino et al. 2019
	Pearl millet flour + Chickpea flour (80:20)	Extrusion; dried 40 °C – 2 h Depigmented millet (soaked 18 h 30–35 °C); Extrusion; dried 40 °C – 2 h	*In vitro* method = pancreatic amylase 37 °C 2 h; liberated maltose dosage [Singh et al., 1982]	30.5 mg maltose released/g pasta 35.6 mg maltose released/g pasta	Rathi, Kawatra, and Sehgal 2004

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Appendix B Table. Continued.

Flours	Formulation	Process	Conditions	Indicators	References
Teff	Teff flour	Extruded; pre-dried 12 min 30 °C and dried 45 °C – 4 h until <10% pasta humidity	*In vitro* method = pepsin 30 min 37 °C + pancreatin, amyloglucosidase and invertase (amylase activity = 7000 U/mL) 37 °C; aliquots during 240 min; glucose dosage [Englyst 1992/ Sun et al., 2006]	RDS = 43 g SDS = 22 g HI = 61 pGI =60	Giuberti et al. 2015
	Teff flour + egg white powder (11%) + emulsifier (1.1%)	Hydration with 50 °C water; Extruded; Fresh pasta	*In vitro* method = pepsin (115 U/ml) 30 min at 37 °C + pancreatic alpha amylase (110 U/ml) 37 °C; aliquots during 300 min; reducing sugars dosage [Brennan 2008]	HI = 43 pGI = 45	Hager et al. 2013
Chickpea	Chickpea flour	Extruded 25 °C 80 bar single layer; dried at 55 °C – 8 h	*In vitro* method = pepsin + pancreatin + amyloglucosidase + invertase 37 °C aliquots during 120 min [Englyst 1992, 1996]	RDS= 7.7 g SDS = 14.5 g	Suo et al. 2022
	Chickpea flour + (White corn flour + Rice flour (ratio 3:2)) (25:75; 50:50; 75:25)			RDS= 10.1–18.6 g SDS = 17–37 g	Suo et al. 2022
	Chickpea flour	Laminated; dried at 45 °C – 4 h	*In vitro* method = alpha amylase (250 U/mL) pepsin (1 mg/mL) 37 °C 30 min; pancreatin (2 mg/mL) and amyloglucosidase (28 U/mL) 37 °C; aliquots during 360 min; glucose dosage [Zheng 2016 method and Englyst 1992 classification]	RDS = 15.0 g/100 g starch (d.b) SDS = 35.4 g/100 g starch (d.b) RS = 49.6 g/100 g starch (d.b)	Garcia-Valle et al. 2021b
	Chickpea flour + DWS (20:80; 40:60; 60:40; 80:20)			RDS = 17.4–21.9 g/100 g starch (d.b) SDS = 37.4–43.5 g/100 g starch (d.b) RS = 34.5–45.2 g/100 g starch (d.b)	
	Chickpea flour + Durum wheat flour (25:75)	Commercial spaghetti	*In vitro* starch hydrolysis method = pepsin 40 °C 1 h + pancreatic alpha-amylase at 37 °C; aliquots during 3 h; glucose dosage [Goni 1997] *In vivo* GI method = 12 healthy females (mean = 23.25 y); blood samples during 120 min after pasta consumption	Starch hydrolysis 180 min = 30–40% of starch GI = 58.9	Goñi and Valentín-Gamazo 2003
	Chickpea flour + DW flour (20:80; 40:60)	Laminated; fresh pasta	*In vitro* method = 6 healthy subjects for the chewing phase + *in vitro* digestion with pepsin and pancreatic amylase; maltose dosage; aliquots during 180 min [Granfeldt et al., 1992]	HI = 61.8–72.5 pGI = 61.5–70.7	Osorio-Díaz et al. 2008
	Black chickpea flour + WS (7:93)	Extruded 50 °C; dried at 55 °C – 8 h		HI = 70%	De Pasquale et al. 2021
	Fermented chickpea flour + WS (17:83)	Fermentation in 30 °C tap water; Extruded 50 °C; dried at 55 °C – 8 h		HI = 60%	
	Chickpea flour + DWS (13.5:86.5)	No coarse fraction; Extrusion 45–50 °C; Dried at 55 °C, duration not know		HI = 70.7%	Schettino, Pontonio, and Rizzello 2019
	Fermented Chickpea flour + DWS (13.5:86.5)	No coarse fraction; Fermentation in 30 °C water; Extrusion 45–50 °C; Dried at 55 °C, duration not know		HI = 55.6%	
	Chickpea flour + Pea flour (40:60)	Commercial pasta «La bona Usanza»	*In vivo* method = 15 healthy subjects; glucose dosage during 120 min [FAO guideline 1998]	GI = 20.1	Turco et al. 2019
	Whole chickpea flour + Unripe plantain + White maize whole flour + CMC (60:25:15/5; 65:15:20/5)	Extruded (50 °C; screw speed: 27.7 rpm); Dried 35–55 °C – 30 h, RH = 95 to 40%	*In vitro* starch fractions method = pancreatin, invertase, amyloglucosidase; 37 °C aliquots during 120 min; glucose dosage [Englyst 1992]; Rate of hydrolysis method = pancreatic alpha amylase 37 °C aliquots during 60 min; maltose dosage [Holm et al., 1985]	RDS = 41.5–43.7 g SDS = 12.2–13.0 g Starch hydrolysis 60min= 40–50% of starch pGI = 76.4–77.1	Bello-Perez et al. 2015

(*Continued*)

Appendix B Table. Continued.

Flours	Formulation	Process	Conditions	Indicators	References
	Chickpea + tiger nut flour (50:50) + fenugreek (replacement of 0–10% of TNF) + eggs 11%	20 min rested at 4 °C after hydration; Laminated; Fresh pasta	*In vitro* method = pepsin 30 min 37 °C + pancreatin, amyloglucosidase and invertase (amylase activity = 7000 U/mL) 37 °C; aliquots during 180 min; glucose dosage [Englyst 1992, 2003]	pGI = 36.3–46.9	Llavata, Albors, and Martin-Esparza 2019
Faba bean	Faba bean flour	Dehulled faba bean; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture	*In vitro* method = method; pancreatic amylase (110 U) 37 °C; aliquot during 180 min [Germaine 2008]	HI = 50.7 pGI = 51.9	Rosa-Sibakov et al. 2016
	Fermented Faba bean flour	Dehulled faba bean; Fermentation 30 °C 48 h; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture		HI = 46.3 pGI = 48.1	
	Faba bean flour + TG	Dehulled faba bean; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture		HI = 19.7 pGI = 25.1	
	Fermented faba bean flour + TG	Dehulled faba bean; Fermentation 30 °C 48 h; Extruded 40 °C; dried 55 °C RH = 88 to 70%, during 15 h to reach 12% of moisture		HI = 30.1 pGI = 34.2	
	Faba bean flour	Dehusked faba bean; Extruded; dried at 55 °C during 12 h to reach 11% pasta moisture	*In vitro* method = pepsin 37 °C 30 min + pancreatin, invertase, amyloglucosidase 37 °C; aliquots during 120 min; HPLC dosage [Englyst et al., 1999]	RAG = 61.8% SAG = 36.4%	Laleg, Barron, Sante-Lhoutellier, et al. 2016
	Faba bean flour + DWS (35:65)	Dehulled FB; Extruded; dried at 55 °C –15 h	*In vitro* method = pepsin 37 °C 30 min + pancreatin, invertase, amyloglucosidase 37 °C; aliquots during 120 min; HPLC dosage [Englyst 1999]	RAG = 59.6%	Petitot and Micard 2010
		Dehulled FB; Extruded; dried at 55 °C – 15 h + HT drying 90 °C – 2 h		RAG = 47.2%	
		Dehulled FB; Extruded; Dried in a lyophilizer		RAG = 86.7%	
		Dehulled FB; Extruded; Precooking in autoclave (120 °C; 1.2 bars; 10 min); dried at 55 °C, duration not know		RAG = 56.8%	
	Faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled FB; Extruded (45–50 °C); dried at 55 °C, duration not know	*In vitro* method = 10 healthy subjects (21–45 y) for the chewing phase + *in vitro* digestion with pepsin and pancreatic amylase; maltose dosage; aliquots during 180 min [Granfeldt 1992]	HI = 64.4–69.3 pGI = 75.2–77.8	Rizzello et al. 2017
	Fermented faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled FB; Fermentation of dough 30 °C during 24 h; Extruded (45–50 °C); dried at 55 °C, duration not know		HI = 62.5–67.9 pGI= 74.0–77.0	

(*Continued*)

Appendix B Table. Continued.

Flours	Formulation	Process	Conditions	Indicators	References
	Faba bean flour + DWS (35:65)	Extruded; dried at 55 °C to reach 12% moisture	*In vitro* RAG/SAG method = pepsin 37 °C 30 min + pancreatin, invertase, amyloglucosidase 37 °C; aliquots during 120 min; HPLC dosage [Englyst 1992/1999]	RAG = 64.9% SAG= 34.4% GI = 41.9 II = 50.1%	Greffeuille et al. 2015
		Extruded; dried at 55 °C to reach 12% moisture + HT drying at 90 °C – 4 h	*In vivo* GI/II method = 15 healthy subjects; blood samples during 180 min after consumption of pasta	RAG = 53.0% SAG = 46.3% GI= 49.4 II = 55.0%	
	Faba bean flour + DWS (10:90; 30:70; 50:50)	Dehulled; Extruded 50 °C; dried 55 °C – 16 h, RH = 50%	*In vitro* method = pepsin (0.1 g/mL) 1 h at 40 °C + alpha amylase (48 U/g) 37 °C; aliquots during 3 h; glucose dosage [Goni 1997/ Sanz-Penella et al., 2014]	pGI = 83.3–89.8	Tazrart et al. 2015
	Whole Dehulled faba bean flour + DWS (25:75)	Dehulled; Extruded (45 °C, screw speed : 25 rpm); HT drying: 75 °C – 18 h	*In vitro* method = pepsin for 30 min 37 °C + pancreatin, alpha amylase and amyloglucosidase; aliquots during 240 min; glucose dosage [Englyst 1992; McCleary 2015]	RDS = 83.0% of starch SDS = 10.5% of starch RS = 6.5% of starch	Gangola et al. 2021
Cassava	Cassava Flour + Hard wheat flour (50:50)	Extruded; dried 45 °C, duration not know	*In vitro* method = pancreatin, invertase, amyloglucosidase; 37 °C aliquots during 120 min; glucose dosage [Englyst 1992; Woo 2002]	RDS = 16.9 g/100 g starch SDS = 21.0 g/100 g starch RS = 60–70 g/100 g starch	Odey and Lee 2019
	Cassava Flour + Wheat flour (50:50)	Fermentation 12, 36 or 60 h at 25 °C in tap water; Extruded; dried 45 °C, duration not know		RDS = 20–30 g/100 g starch SDS= 20–40 g/100 g starch RS = 35–45 g/100 g starch	
Pigeon Pea	Pigeon pea + Brown rice (10–30:70–90)	Cooking extrusion (30, 40, 50, and 70 to 110 °C in the 4 sections, respectively, twin screw); dried 50–60 °C, duration not know	*In vitro* method = pancreatic amylase 37 °C 2 h; maltose dosage [Onyango et al., 2004]	Starch digestibility 120 min = 15.0–26.8% of starch	Rafiq, Sharma, and Singh 2017
Sweet potato	Sweet potato flour + Refined wheat flour (79:21; 82:18; 85:15) + apple fiber (10–20%) + whey protein concentrate (10%) + oil (5%) + XG (0–1.5%) + ascorbic acid (0.5%) + glyceryl monostearate (0.1%)	Extruded; dried at 50 °C during 18 h until <12% of pasta moisture	*In vitro* method = Pepsin 1 h 37 °C + lipase (2000 U/sample) amylase (1800 U) and protease (100 U) 37 °C; aliquots during 120 min; glucose dosage [Englyst 1992, 1996; McCleary and Monaghan, 2002; Kim 2008]	Starch digestibility 120 min = 51.7–76.8% of starch RDS = 34.9–55.7% of starch SDS = 8.0–16.2% of starch	Menon, Padmaja, and Sajeev 2014
	Sweet potato flour + Refined wheat flour (88:12) + whey protein concentrate (10%) + oil (5%)			Starch digestibility 120min = 73.6% total starch RDS = 48.5% of starch SDS = 17.7% of starch RS = 33.8% of starch	Menon, Padmaja, and Sajeev 2015
	Sweet potato flour 50 or 60% (cream fleshed or orange fleshed) + Refined wheat flour 27% (65:35; 69:31) + fiber sources (oat, wheat and rice bran) 10 or 20% + gelatinized cassava 3%	Peeled SP; Soaked in acetic acid 1 h to prevent discoloration of flour; Extruded; dried at 50 °C – 18 h		RDS = 37.3–69.7% of starch SDS = 2.6–16.6% of starch RS = 14.7–54.7% of starch	Krishnan et al. 2012
	Orange fleshed sweet potato flour + White maize flour (20:80; 30:70; 50:50)	Extrusion cooking (twin screw; T° = 60, 70, 80, 80, 80 for zones 1, 2, 3, 4 and 5; screw speed = 80 rpm); Dried at ambient T° overnight	*In vitro* method = Pepsin 40 °C 1 h + shaker water bath 37 °C 30 min + pancreatic amylase (2.6 U) 37 °C; Aliquots during 180 min; glucose dosage [Englyst 1992; Goni 1997; Mapengo and Emmambux, 2020]	Starch hydrolysis after 180 min = 83.1–96.7% RDS = 72.0–82.4% SDS =4.67–15.6% RS = 9.32–2.3%	Baah, Duodu, and Emmambux 2022

CMC: carboxyl methyl cellulose; d.b: dry basis; DW: durum wheat; DWS: durum wheat semolina; Extruded: low temperature extrusion; GG: gum guar; GI: glycemic index; HI: hydrolysis index; HT: high temperature; II: insulin index; pGI: predicted glycemic index; RAG: rapid available glucose; RDS: rapidly digestible starch; RS: resistant starch; SAG: slowly available glucose; SDS: slowly digestible starch; TG: transglutaminase; w.b: wet basis; WS: wheat semolina; XG: xanthan gum; y: year; RDS/SDS/RS: values are given in g/100 g of pasta (d.b); RAG/SAG: values in % of available carbohydrates (carbohydrates − resistant starch).