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Nutritional Value of Legume Crops for Humans and Animals

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Abstract. Food legumes are important sources of nutrients and provide supplementary protein to diets based on cereal grains and/or starchy foods. Protein, provided mainly by the cotyledons, ranges in concentration from about 17% to 40%. These crops are significant sources of phosphorus, iron, and/or certain water-soluble vitamins; the total amount of fat they contain is relatively small, but is extremely unsaturated. The protein in legume foods is deficient in sulphur amino acids, although it is relatively rich in lysine. The concentrations of these nutrients are affected by environmental and genetic factors. Some information is available for a few species on the interrelationships between agronomic and genetic characteristics and the concentration of specific nutrients, such as protein and sulphur amino acids. These relationships cannot be generalised for all legume species or even within the same species, and additional studies are needed. Some correlations have been established between chemically determined nutrient values and biological results but, again, more observations are required.

Nutritive values of the protein for humans are essentially similar to those reported from experiments with animals. Legume protein is relatively indigestible, and has a poor biological value which can be significantly improved by methionine supplementation. Nutritionally, the most significant attribute of legume foods is their supplementary effect on diets otherwise composed largely of cereal-grain protein. This characteristic should be maximised by increased availability and improved protein digestibility and sulphur amino acid content. The reasons for the relatively poor protein digestibility of cooked materials are not well defined but tannin content may be important. Other nutritional attributes such as the hypocholesterolemic effects should be exploited. Beans must be acceptable if intake is to improve and supplementary effects are to be maximised. However, the problem of hard seed coats and its consequences in processing must receive more attention. Without doubt, beans offer excellent opportunities for productive interaction between agricultural scientists, nutritionists, and food technologists.

I. Introduction

The benefit which grass and forage legume combinations provide in the maintenance of soil fertility, owing to the ability of the legume to fix nitrogen biologically, have long been recognised in agricultural practices. Likewise, grass–legume associations are recommended and utilised for improved nutrient intake by cattle, because the legume can concentrate foliar protein and therefore provides animals with a greater protein intake. It is perhaps no surprise, then, that appropriate combinations of cereal and legume grains can provide a balanced protein nutrition for humans. The legume seed accumulates proteins which are an appropriate supplement to the protein in cereal grains. In all these situations, and in particular the latter two, the quality of the legume crop, whether forage or seed, is of the utmost importance; more so for the nutrition of monogastric animals such as humans. However, attempts by agronomists and plant breeders to improve the nutritional quality of legume seeds, and protein in particular, are relatively recent and far less is known about these important food crops than is known about cereal grains.

II. Chemical composition and amino acid content

Although seeds of only about 20 of the 12,000 or so recognised legume species are cultivated and consumed, they represent an important source of proteins and other nutrients.

A. Chemical composition

Legume seeds are generally characterised by a relatively large content of protein, which varies between 17% and 40%, an even greater concentration of carbohydrate, and a small oil content (Table I). The protein is mainly located in the cotyledons and embryonic axis of the seeds, with small amounts present in the testa. For example, testas of many beans contain about 4.8% crude protein, while the cotyledons and the embryonic axis have 27.5% and 47.6% respectively. Because of their greater weight, cotyledons contribute the major proportion of the protein of whole seeds.

Table I. Composition of legume seeds (% dry weight).

Legume species	Protein	Ether extract	Crude fibre	Ash	Carbohydrate
Vigna unguiculata	27.5	2.1	7.0	4.9	58.5
Cajanus cajan	21.8	1.7	8.7	3.8	64.0
Phaseolus vulgaris	26.1	1.8	6.6	4.1	61.4
Vinga umbellata	23.9	0.8	8.3	4.4	62.6
Phaseolus lunatus	26.4	2.7	6.7	3.7	60.5
Phaseolus lunatus	23.5	1.4	5.6	4.2	65.3
Vigna radiata	25.6	3.0	3.5	3.0	64.9
Psophocarpus sp.	37.6	22.5	13.8	4.4	21.7
Pisum sativum	28.8	1.6	6.7	2.9	60.0
Cicer arietinum	20.6	7.0	3.8	3.4	65.2
Lens culinaris	29.6	3.1	3.2	2.4	61.7
Cajanus cajan	22.9	3.8	5.0	4.1	64.1
Cyamopsis tetragonoloba	34.4	3.9	5.2	3.6	59.9

The lipid content of legume foods comprises a relatively small proportion of the overall composition and varies from 1% to 6% depending on the species. The glyceride fractions consist mainly of the unsaturated oleic, linoleic, and linolenic fatty acids.

The ash content of legume foods ranges from 2.5% to 4.2%. Among the minerals, phosphorus occurs in the largest amounts and averages about

300 mg (100 g)$^{-1}$ in beans. The calcium content is only about 100 mg (100 g)$^{-1}$ hence legume seeds are a relatively poor source of this nutrient. However, iron content varies from 5 to 12 mg (100 g)$^{-1}$, which classifies legume seeds as an important source of this mineral. Nevertheless, very little is known about its availability after ingestion by the animal organism. Because these nutrients, especially iron, are deficient in diets consumed by several population groups in some countries, this aspect needs further investigation. Such research should apply to mature and immature, as well as germinated, seeds since these are all consumed in various locations.

Legume foods are considered to be significant sources of thiamine, riboflavin, and niacin, which are mainly located in the germ rather than in the cotyledons. Other vitamins of the B complex group as well as ascorbic acid, vitamin K, and tocopherols, are also present. The concentrations of each of these vitamins increase during germination, indicating the benefits of this process on the nutritive value of legume grains [12].

B. Interactions of environmental and genetic factors on chemical composition

A number of studies on various legumes have recorded interactions between environmental and genetic factors on chemical composition and nutritive value [19, 30, 31, 32, 34, 38, 44, 45, 46]. Some representative findings which are applicable to all legume seeds and which may be generalised are shown in Table II. Most reports show that environmental factors not only influence yield but also affect protein content and sulphur amino acids. Thus protein quality is also affected. Bean yields are negatively related to seed protein concentration but are still positively related to protein yield. The application of NPK fertiliser, *Rhizobium* inoculation, and increased plant density can each increase yields but do not change protein quality. On the other hand, P applications and *S*-triazine herbicides increase protein and free amino acids although these effects have not been evaluated biologically. Other relationships between seed yield and seed protein content are shown in Table III. These apply for *Phaseolus,* although it is possible that other species of legumes will behave similarly [13, 34, 39, 42]. In addition, genetic factors are known to influence protein quality as measured chemically but it is difficult to indicate the role of protein amino acid balance *per se* on protein quality and its interaction with other factors in beans. These aspects all require more detailed study.

Table III Some relationships between agronomic characteristics and protein content in *Phaseolus vulgaris*.

Seed protein concentration (%) – negatively correlated with bean yield ha^{-1}
Protein yield ha^{-1} –positively correlated with bean yield ha^{-1}
Total seed protein content – positively correlated with mean seed weight
Seed protein concentration (%) – sometimes negatively correlated with mean seed weight

Table II Summary of results reported on the effects of environmental and genetic factors on the yield, protein quantity and quality of legume seeds.

Factor	Yield	Protein (%)	Methionine (%)	Protein quality
Environmental				
Location-year	Affected	Affected	Affected	Affected
Cultural practices				
NPK fertilizations	Increase	No change	No change	Not evaluated
P applications	Increase	Increase	No change	Not evaluated
Rhizobium inoculation	Increase	Not affected	Not affected	Not affected
Crop density	Affected	No change	No change	–
S applications	Increase	No change	Some	Some
Triazine applications	–	Increase	Change	Not evaluated
Genetic	Affected	Affected	Affected	Affected

C. *Amino acid content*

All edible legume seeds have been analysed for their amino acid content, and the variability for the most common species in the limiting amino acids is presented in Table IV [32]. This variation is due to genetic and environmental factors [12] but cultural practices and seed maturation may also be important [8, 22, 46]. Calculations of amino acid scores, as well as biological tests with animals, show that although legume proteins are deficient in sulphur-containing amino acids they are relatively rich in sources of lysine. The beneficial effect of methionine supplementation on the protein quality of legume foods is well established but, in pigeon peas (*Cajanus cajan*), the simultaneous addition of both methionine and tryptophan is required [10,29].

Table IV Reported ranges of limiting amino acid contents (mg(gN)$^{-1}$) in legume seeds [from 32].

Amino acid	Common bean	Soyabean	Groundnut	Cowpea	Chick pea
Methionine	28–131	53–114	33–100	50–119	34–106
Cystine	21–108	51–114	11–106	48–106	50– 94
Tryptophan	32–101	75– 88	45– 90	66– 70	25– 94
Valine	213–388	250–375	142–307	250–325	213–356
Threonine	192–356	200–285	116–207	178–300	219–263

Breeding legumes for increased protein quality, viz. a simultaneous selection for large yield and improved methionine content, has progressed only to the establishment of the range of variability available and determination of whether or not amino acid content is genetically controlled.

For some legume species, collections with various numbers of entries have been analysed for potential nutritional value [4, 33, 39]. An example is shown in Fig. 1, for a collection of *Phaseolus vulgaris* from Central America (Bressani *et al.*, unpublished). There is a normal distribution for protein, as well as for methionine, cystine, and lysine concentrations. From such information, relationships between nutrients have been established and are summarised in Table V. Sulphur amino acid contents, either individually or in total, are negatively related to protein content in *Vigna* and *Phaseolus* [1, 5, 6, 8, 26, 40, 43]. Of interest is the positive significant correlation between total sulphur content and total sulphur amino acids, which may facilitate screening of large germplasm collections.

Assessments of protein quality should be based on chemically determined relationships but even chemically derived data may not give clear relationships as shown in Table VI for a study of 127 cultivars of *Phaseolus vulgaris* (Bressani *et al.*, unpublished). These data show that only cystine concentration is negatively related to protein content for all beans, irrespective of testa colour. Methionine and lysine concentrations are negatively related

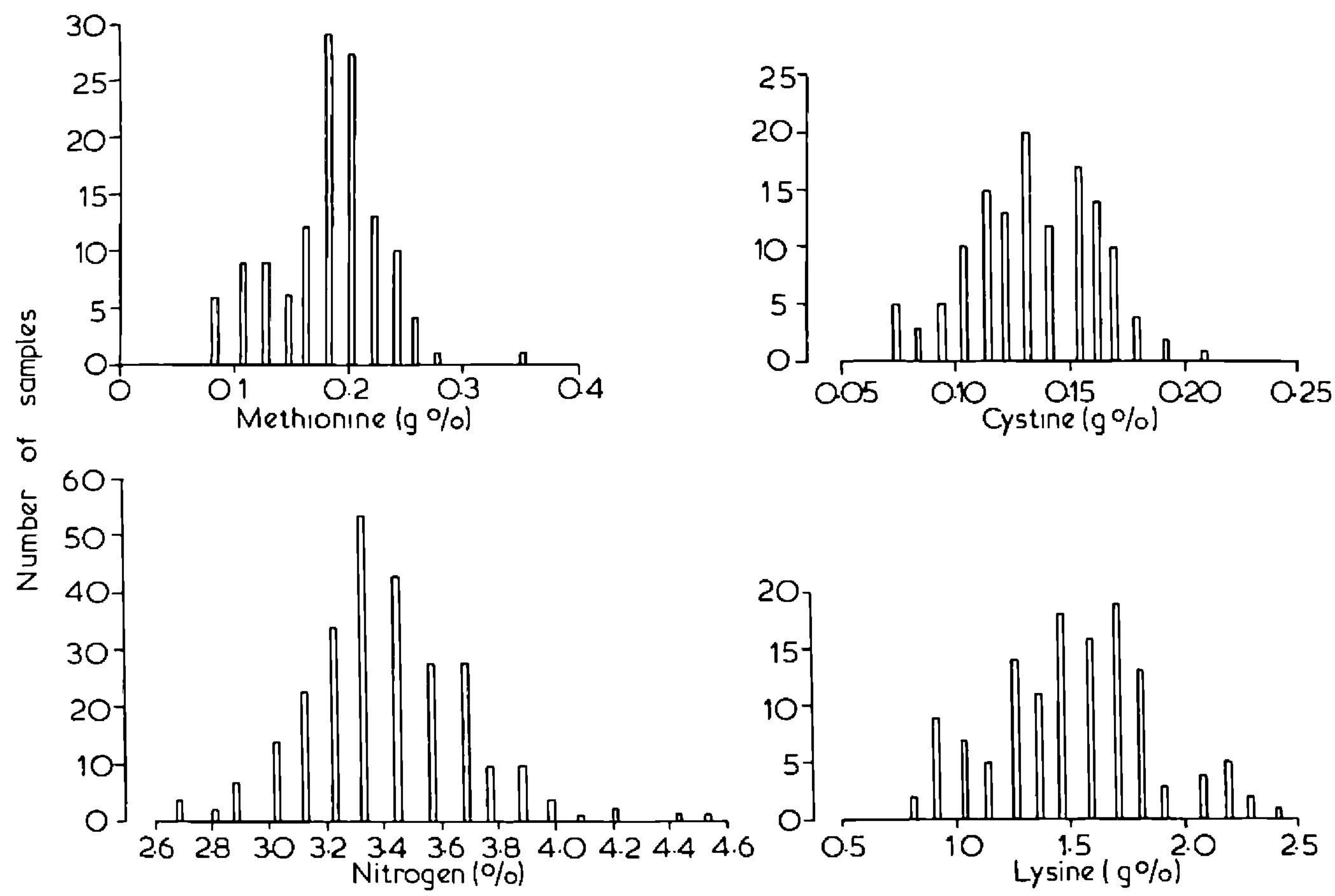

Fig. 1 Distribution of methionine, cystine, and lysine (g %) and of nitrogen (%) in *Phaseolus vulgaris* genotypes from Central America.

Table V Relationships between protein content and sulphur amino acids, total sulphur and protein quality in legume seeds.

Nutrients	Correlation		Species	Reference
Protein (%) *vs* Methionine (%)	N	S	*Vigna* *Phaseolus*	26 1
Protein (%) *vs* Cystine (%)	N	S	*Phaseolus*	1, 11
Protein (%) *vs* T. S. A. A. (%)	N	S	*Vigna* *Phaseolus*	27 1, 11
T. S. A. A. (%) *vs* T.S. (%)	P	S	*Vigna* *Phaseolus* *Cicer*	27 40 43
Protein (%) *vs* Protein Quality	N none none	S	*Phaseolus* *Vigna* *Pisum*	11 11 5, 6
Albumin (%) *vs* Protein Quality	P	S	*Pisum*	
T. S. A. A. (%) *vs* Protein Quality	P	S	*Phaseolus*	11, 40

N: Negative
P: Positive
S: Statistically significant

T.S. and T.S.A.A. denote total sulphur and total suphur-containing amino acids, respectively.

Table VI Relationship between protein content (%) and methionine, cystine and lysine contents (%) in 127 cultivars of *Phaseolus vulgaris* from Central America.

	Testa Colour				
Nutrients	White	Beige	Black	Red	All
Protein *vs* Methionine	+ NS	+ S	- NS	- NS	- NS
Protein *vs* Cystine	- S	- S	- S	- S	- S
Protein *vs* T.S.A.A.	- S	+ NS	- NS	- S	- S
Protein *vs* Lysine	+ NS	+ NS	- NS	- NS	- NS

NS: Not significant
S: Significant
T.S.A.A. denotes total sulphur-containing amino acid content.

to protein content in black- and red-seeded types but the relationship is not statistically reliable. In beige- and white-seeded types methionine and lysine concentrations are positively related to protein content although again the correlation was not always significant. Positive correlations have been reported between pairs of amino acids which suggests that selection for one could be effective for both [20, 46]. These relationships may provide a useful selection tool particularly if analytical techniques are easier to perform for one of the amino acids.

There are two possible ways to improve protein quality: (a) to establish whether sulphur amino acid concentrations *per se* are genetically controlled; and (b) to establish if genes regulate individual protein distribution in legume seeds; and then to select for a greater proportion of those proteins with larger contents of S-amino acids (see also Boulter, this volume). Evidence to support the latter approach is already available [6, 9]. Of particular interest is that protein quality in peas can be predicted from the albumin content [6] or from the globulin:albumin ratio; the albumins are richer sources of methionine than globulins. Another possibility would be to select for a larger content of alcohol-soluble proteins, which represent about 10% of the total protein. This fraction contains relatively large amounts of sulphur amino acids, at least in cereal grains.

Finally, chemical relationships should be reflected in biological assays, but this is not always the case. For example, the effects of cooking and subsequent dehydration may decrease amino acid availability. Other important factors could be the presence of tannins, the stage of seed maturity, and even differences between crude and true protein contents. The results in Fig. 2 were obtained from nine cultivars of *P. vulgaris:* five black-, two red-, and two white-seeded. Protein content and net protein ratio are negatively related but one black-seeded cultivar with 22.7% protein gave a much smaller value than a sample with 24.2% protein. Total sulphur amino acid content is also

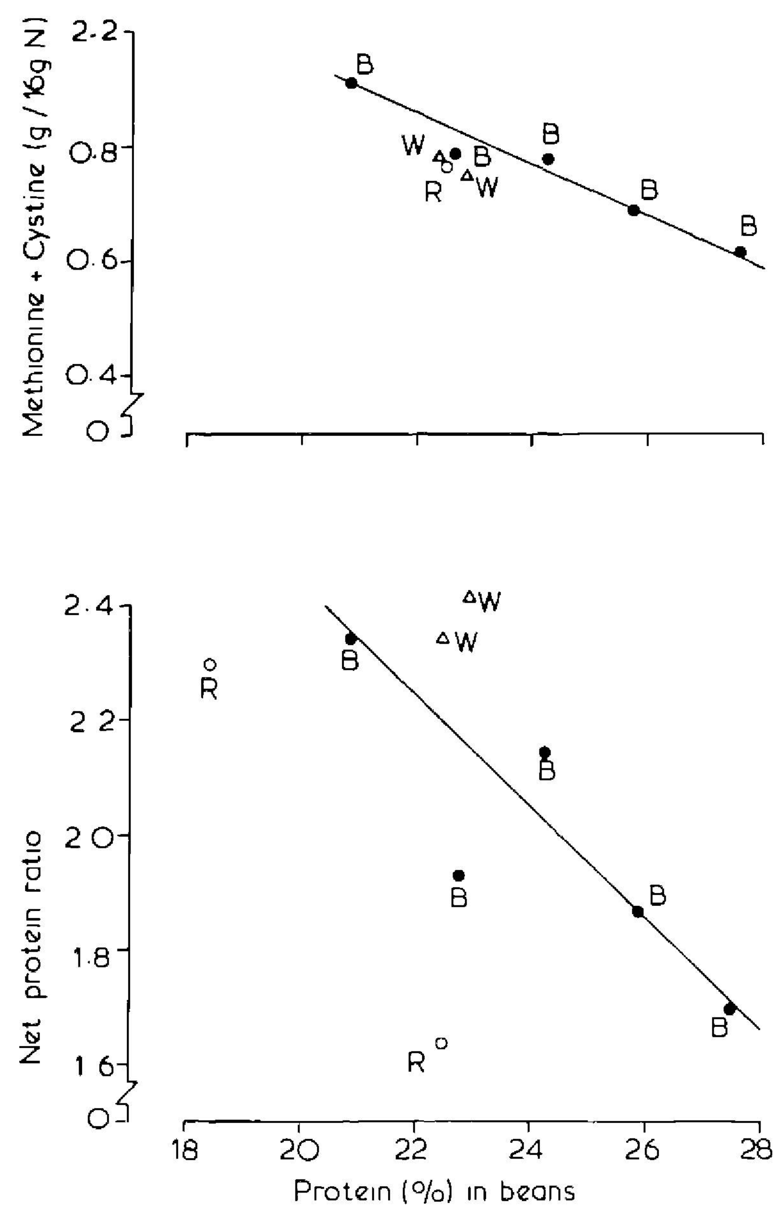

Fig. 2 Relationship between protein content (%) and (above) total sulphur-containing amino acids $(g(16gN)^{-1})$ and (below) net protein ratio in nine cultivars of *Phaseolus vulgaris*. Testa colours are denoted by W, R, and B for white, red, and black, respectively.

negatively related to protein content and is likely to be positively correlated with protein quality. In this study tryptophan was positively correlated with protein quality, but lysine was not [13].

It is not safe to generalise from these relationships to all legumes. For example, with nine *Vigna* cultivars no relationship was found between protein and sulphur amino acid contents, and neither was related to protein quality [21]; and no relationship was found between protein content and protein quality in pea seeds [5, 6]. Therefore, other factors must be considered in order to establish relationships between chemical data and biological value. In the case of peas, the proportion of cotyledonary nitrogen in protein varies with seed maturity.

Research in this area should aim to improve the chemical and *in vitro* methods used to assay amino acid content and availability, especially for the total sulphur amino acids. Many more studies are required to establish much better relationships than those shown here to compare chemical characteristics with biological parameters.

D. *Protein quality in human nutrition*

Most studies on the protein quality of legume seeds have been with animals, particularly with rats reared in laboratory conditions. These studies permit several conclusions:

(a) Only those legume foods that contain small amounts of antiphysiological factors, or are free from them, can be evaluated raw. Appropriate cooking causes destruction or inactivation of antiphysiological factors and is necessary to measure protein quality. In some cases other processes, such as extrusion, induce further increases in protein utilisation (see also Liener; Nowacki; and Boulter, this volume).

(b) Protein quality, however measured, varies between species and between cultivars of the same species. Values range from 0.5 (*P. vulgaris*) to 2.4 (soyabean).

(c) All legume foods, irrespective of their initial protein quality, are improved by methionine supplementation. The second most important limiting amino acid is tryptophan in many species or threonine in a few.

(d) The poor protein quality of legume seeds is mainly due to sulphur amino acid deficiency but protein digestibility may also be important and varies between species and within cultivars of the same species.

With humans, some information is available but only for a limited number of legume species. Table VII summarises the evaluation in young adult humans fed either peas alone or peas with a methionine supplement. Nitrogen intake from eggs or peas was the same but methionine supplementation promoted a dramatic increase in nitrogen retention [25]. Also in adults, and using a multiple point protein assay, there is no difference in NPU between

Table VII Nitrogen balance in young adult human subjects fed *Pisum sativum* [from 25].

Protein source	N intake	N balance
	g day^{-1}	
Egg	5.60	-0.11 [a]
Pisum sativum	5.47	-0.31 [a]
Pisum sativum + Methionine	5.95	-0.55 [b]

Numbers followed by the same letter are not significantly different.

milk and soyabean protein (Table VIII) but *P. vulgaris* protein is significantly inferior [13]. It is of interest that the nitrogen absorbed from beans has a comparable quality to milk and soyabeans. Other studies with children (Table IX) indicate that the quality of bean protein is extremely poor compared with milk [41]. Methionine supplementation of soyabean protein increases nitrogen retention in young and adult human subjects [2]. Therefore, the results with humans agree quite well with those obtained from laboratory animals.

Table VIII Quality of *Phaseolus vulgaris* and soyabean protein in young adult human subjects [from 15].

Protein source	NR = a + b (NI)	NR = a + b (NA)
P. vulgaris	-62.7 + 0.54 (NI)	-57.4 + 0.81 (NA)
Milk	-72.3 + 0.82 (NI)	-57.2 + 0.93 (NA)
Soyabean protein	-72.2 + 0.83 (NI)	-56.3 + 0.91 (NA)

NI, NA and NR denote intake, absorption and retention of nitrogen, respectively.

Table IX Nitrogen balance in children fed *Phaseolus vulgaris* [from 41].

Protein source	N intake ($g\ kg^{-1}\ day^{-1}$)	N balance ($mg\ kg^{-1}\ day^{-1}$)
Milk	236	74
Cooked beans	227	37

III. Significant nutritional characteristics of grain legumes

A. Supplementary effect of beans to cereal grains and starchy foods

Food intake patterns in many tropical countries reveal that beans are usually consumed with cereal grains – mainly rice and maize, or with cassava and plantains. When eaten with cereals, beans provide both a larger protein intake and amino acids that significantly improve the protein quality of the cereal grain–bean mixture. Cereal and bean proteins complement each other very effectively: the latter provides more lysine and the former supplements methionine. In the starch food–bean system, the role of beans is more critical and although they provide more total protein they fail to increase protein quality because of the deficiencies in sulphur amino acids in both dietary constituents.

Cereal–bean mixtures. Maximum protein quality values of rice and beans are shown in Fig. 3, and are obtained when 80% of the total protein is derived from rice and 20% from beans, either *Phaseolus vulgaris* or *Vigna mungo* [4, 16]. Supplementation with the limiting amino acids increases quality in every case. Addition of methionine alone to beans is less effective than when blends of several amino acids are provided; the bean diet suffers also from poor digestibility.

Additional examples for maize and different species of beans are shown in Fig. 4 [11]. All diets show maximum quality values when each component provides equal amounts of protein to the total. The differences between

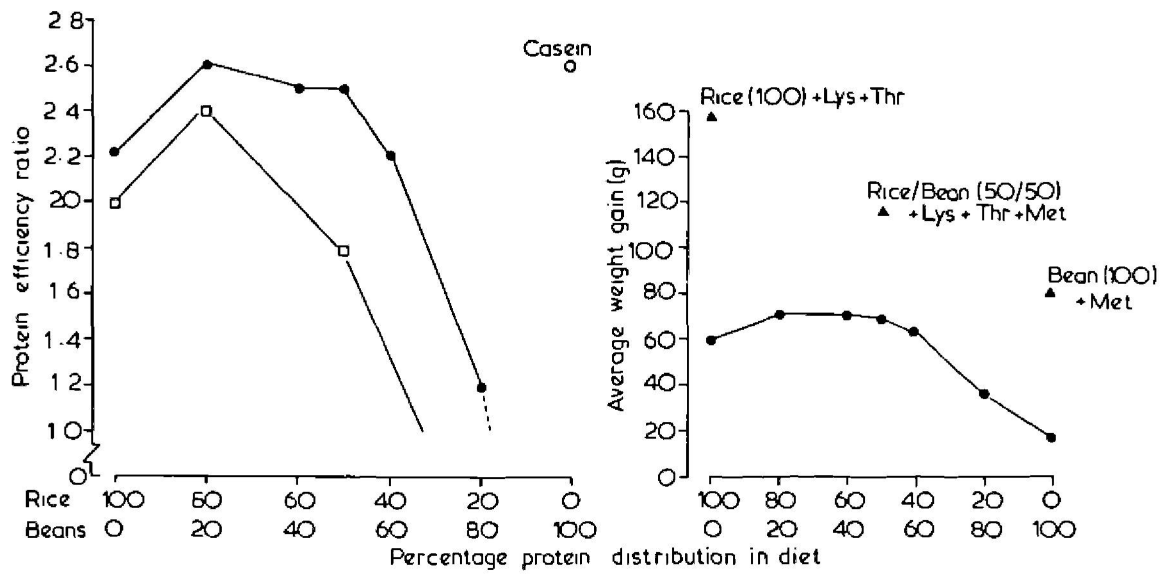

Fig. 3 Protein complementation between legume seeds and rice. Solid circles = *P. vulgaris*; open squares = *Vigna mungo*.

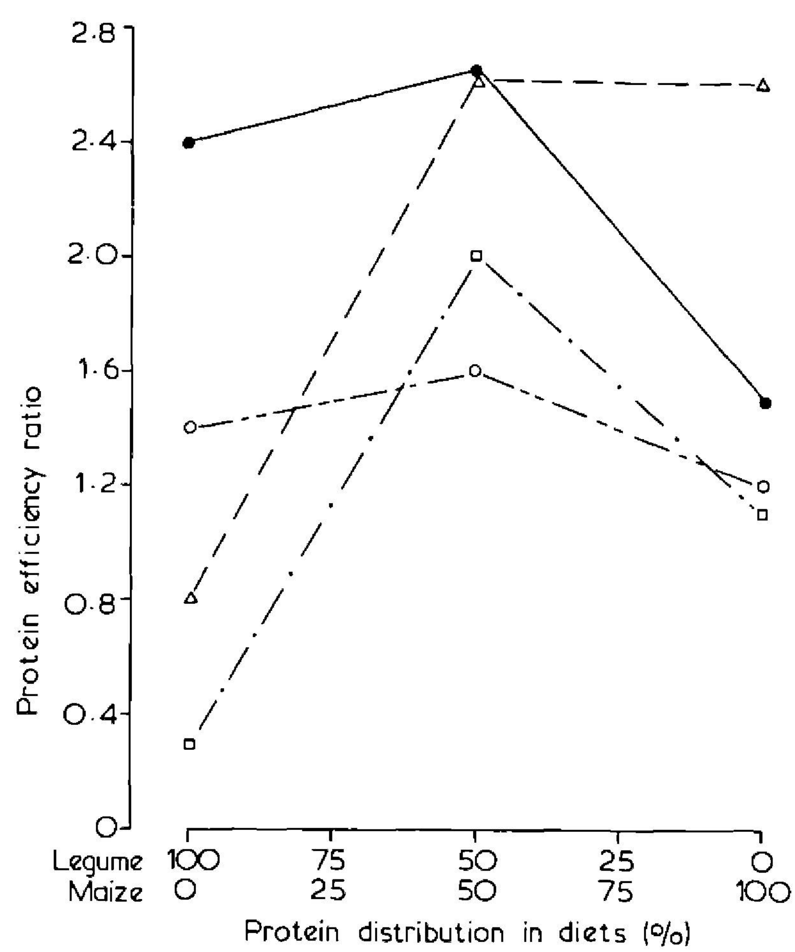

Fig. 4 Protein quality of mixtures of maize and legume seeds. Symbols: solid circles, open circles, triangles and squares denote mixtures of maize with soyabeans and cowpeas, and common beans with Opaque 2 and conventional maize, respectively.

common beans and soyabeans is due to larger contents of methionine and tryptophan as well as improved protein digestibility in soyabeans. Differences in the exclusively cereal diets are due to large lysine and tryptophan contents in Opaque-2 compared with common maize. Thus, any blend that includes more than 50% legume protein is mainly deficient in methionine with a secondary deficiency in tryptophan whereas any blend which comprises more than 50% maize protein is deficient primarily in lysine and, to a lesser extent, in tryptophan.

Figure 5 summarises data from a very large number of biological studies with animals, but few of these results have been confirmed with humans [11, 17]. The Figure provides additional information on how to increase the nutritional protein value of diets based on maize and beans, viz.

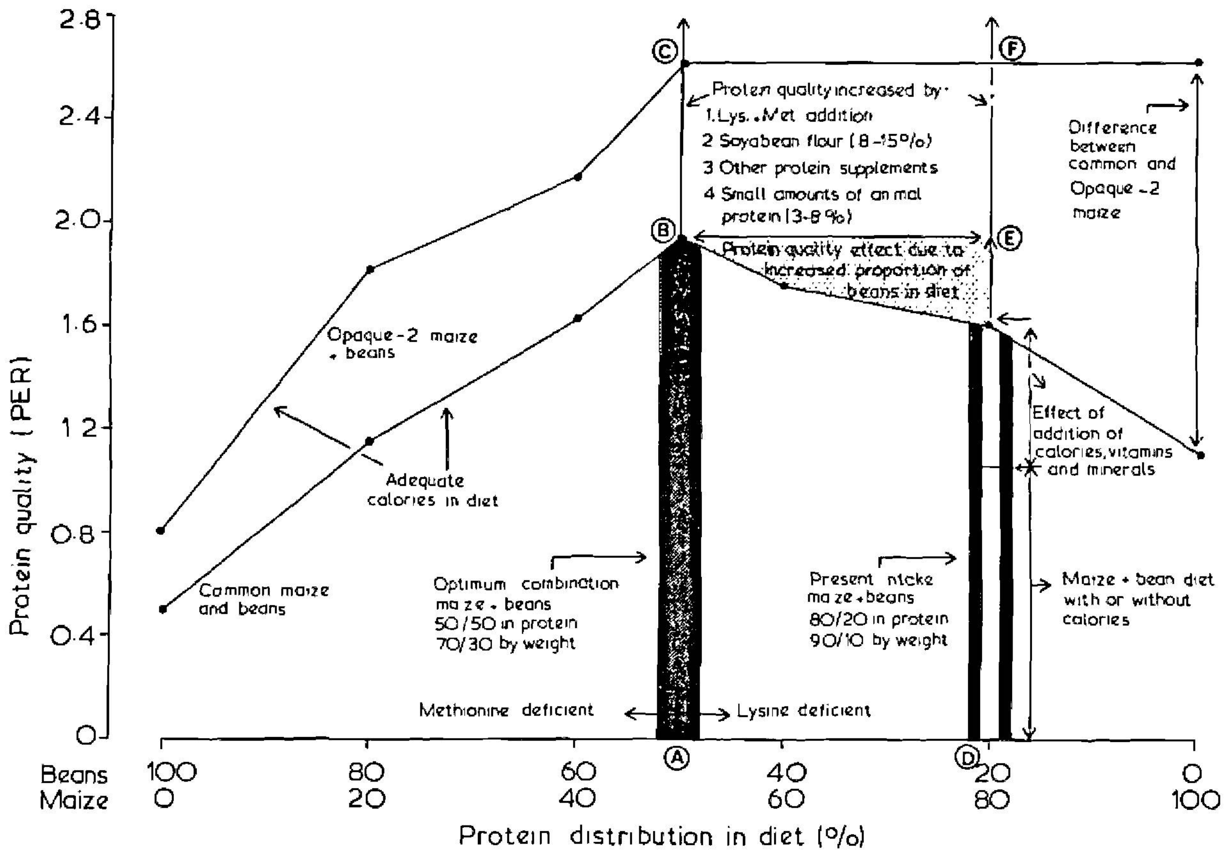

Fig.5 The maize–bean food system and its improvement.

(a) To attain bean consumption A and thus protein quality B it is necessary to increase both the productivity of beans per hectare and their availability.

(b) To attain bean consumption A but improved protein quality C it is necessary to increase productivity and availability of beans that contain larger concentrations of total sulphur amino acids and tryptophan. The alternative is to provide foods with a protein quality as indicated in Fig. 5.

(c) To maintain bean intake D with protein quality E or F it is necessary not only to increase tryptophan concentrations in beans with minor increases in total sulphur amino acids but also to maintain a large lysine content and biological availability. The alternative is to provide supplementary protein foods as shown in Fig. 5.

(d) To maintain bean intake D with protein quality between E and B, it would be necessary to produce beans with a larger protein content but with the same amino acid pattern. However, it would be significantly better if improved protein content also involved larger concentrations of sulphur amino acids, tryptophan and lysine.

Thus, if beans were more available and cheap, an intake ratio of 70:30 maize and beans would provide a well balanced diet for humans. Alternatively, this approach may also be useful to screen beans for improved protein quality. The results shown in Fig. 6 demonstrate this possibility [13]. In this study, five cultivars of *P. vulgaris* with black seed coats were tested alone or as a component of a maize/bean diet with either 10% or 30% beans. When beans

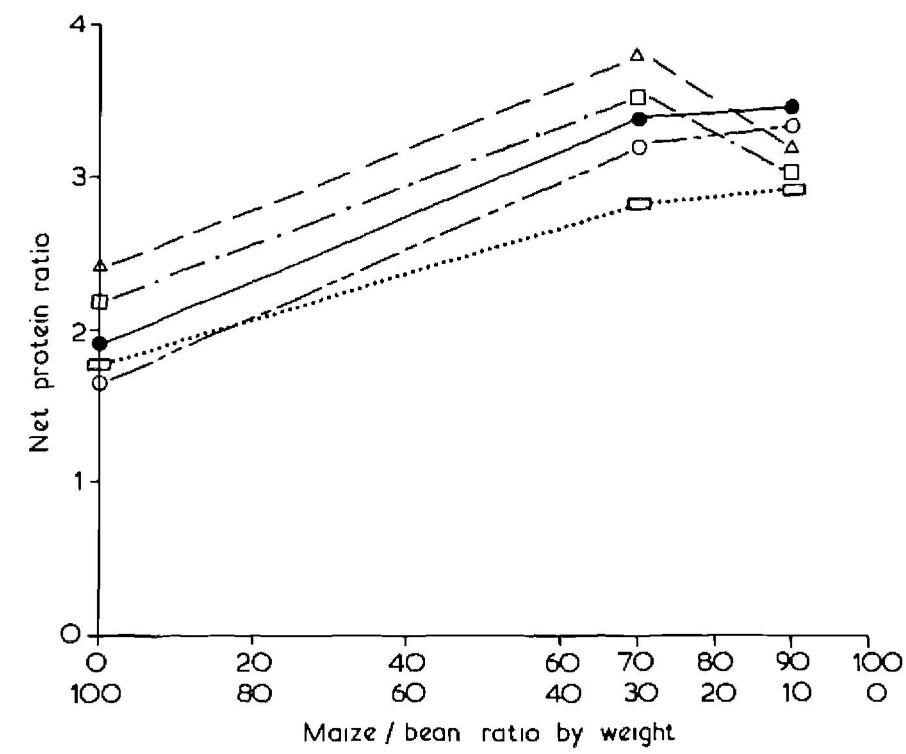

Fig. 6 Protein quality (NPR) of five black-seeded cultivars of *P. vulgaris* fed alone or in mixtures with maize.

were fed alone, protein quality (as measured by NPR) varied from 1.71 to 2.34, but this is no indication of how well or to what extent they will supplement maize proteins, either at 10% or at 30% in mixtures. Furthermore, three of the five cultivars were no more effective when used at 30% than when tested at 10%. These cultivars were the poorest quality when fed alone. The correlation between protein quality values when beans were fed alone, and at 10% of the total diet, was poor, but improved, as expected, as more beans were included in the diet.

These results also show a negative relationship between protein quantity and quality. The poor quality beans gave maximum improvement at 10%, while the better quality beans were more effective when they comprised 30% of the diet. These studies must be confirmed, but they do show the problems faced when attempts are made to select beans for improved protein quality. It appears that for cereal grain diets, beans with 22–23% protein and a large sulphur amino acid content would be better than those with larger protein concentrations but a smaller sulphur amino acid content.

The improved protein quality of mixtures of maize and beans in a 50:50 protein ratio has also been demonstrated in children (Fig. 7). In this example, four children were fed initially (Phase 1) a 76:24 maize–bean diet and nitrogen balances were determined [7]. Later on, more beans were provided and as the proportion of beans increased in this diet nitrogen retention values improved. A blend of 50:50 maize–bean protein gave the largest nitrogen retention.

B. Beans as a protein source for starchy diets based on cassava or plantains

The practical significance of protein quantity and quality in legume seeds is especially important in diets based on starchy food products such as plantains, cassava, or yams (Fig. 8). These data show that 30 g of beans and 70 g of cassava flour are needed for rats to maintain body weight. However, 26 g of

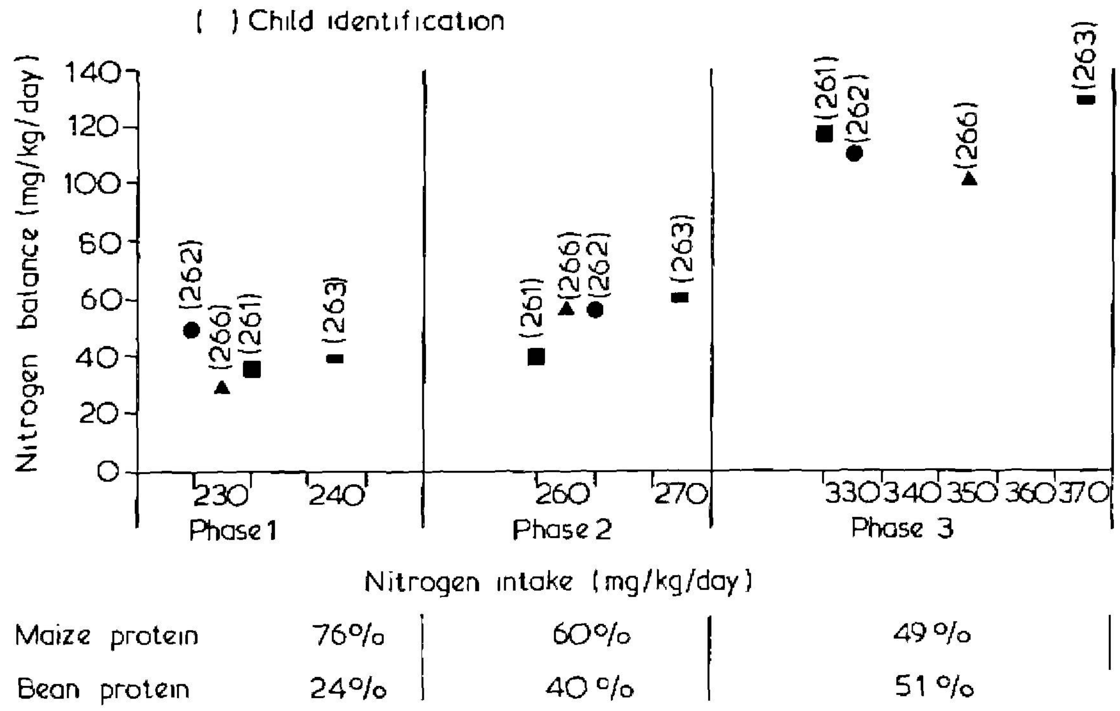

Fig. 7 Nitrogen balance (mg kg^{-1} day^{-1}) of children fed various mixtures of maize and beans. Symbols identify the children and their nitrogen balance.

beans but with a larger amount of methionine would be more effective than 39 g with the normal concentration of this amino acid. An improved quality of the protein in beans would have significant impact in the utilisation of diets based on starchy foods [11].

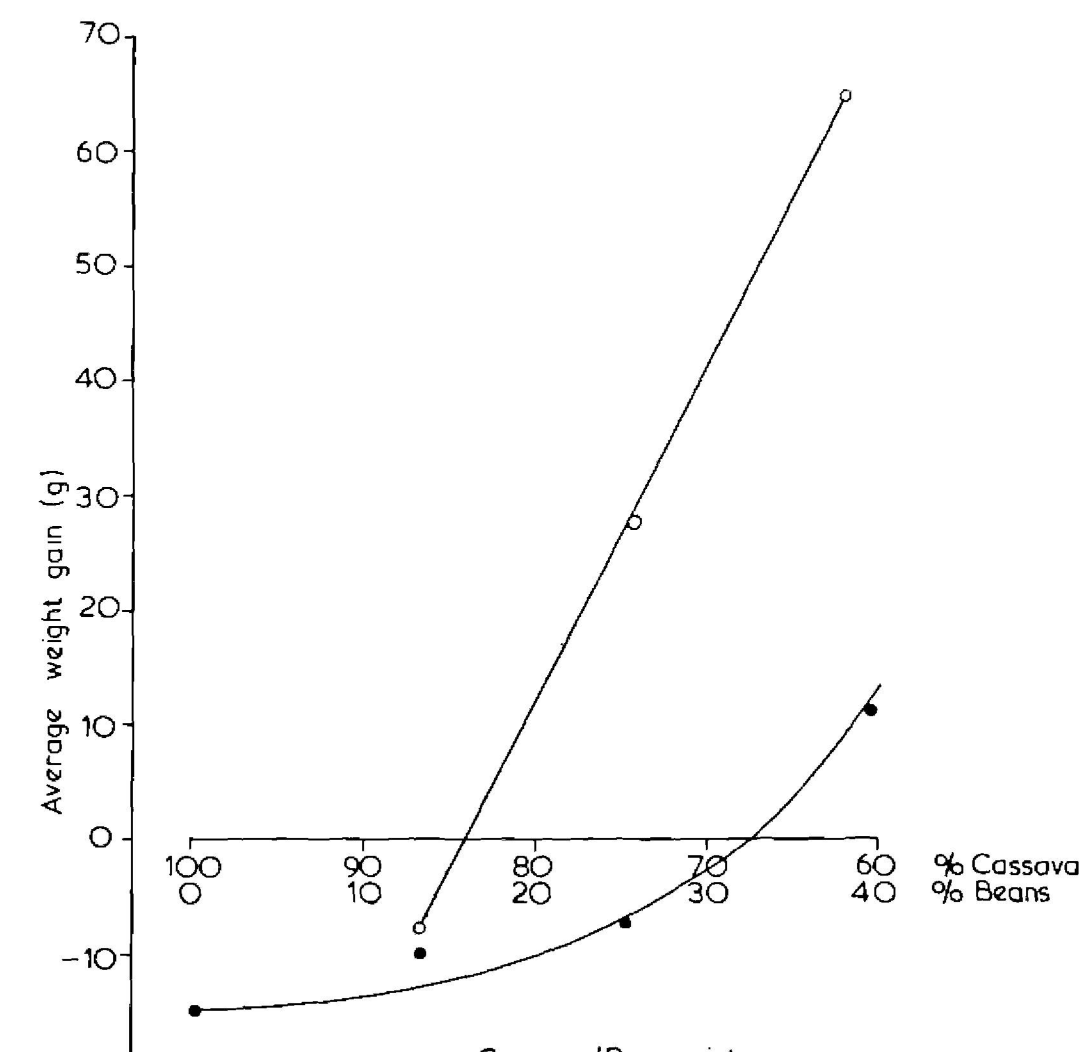

Fig. 8 Nutritional significance of bean protein quantity and quality in cassava based diets; solid and open circles denote absence and presence of methionine supplementation, respectively.

C. *Other nutritional characteristics*

A few years ago it was observed that bean feeding reduced the concentration of cholesterol in human subjects. More recently, studies with soyabean protein have demonstrated a similar effect. Although few observations have been made, the hypocholesterolemic effects of legume seeds should be studied further. No explanation of this effect is currently available but it seems not to be related to the methionine deficiency in legume seeds [28].

IV. Problems of nutritional interest in food legumes

In addition to the problem of sulphur amino acid deficiency of legume seeds, the more efficient utilisation of the nutrients in these staples is dependent on protein digestibility and cooking characteristics.

A. *Legume protein digestibility*

Protein digestibility is related to various factors which include:

(a) the presence of antiphysiological factors such as trypsin and amylase inhibitors and haemagglutinin compounds;

(b) the presence of tannins, whose function at present is not well known (see also Liener, this volume).

The protein digestibility of various legume seeds is shown in Table X as determined for rats [12]. There is considerable variation not only between species but also within the same species: for example, in *Cajanus*, the values range from 47.7% to 75.3%. The difference between raw and cooked samples

Table X Protein digestibility (%) of some raw and cooked legume seeds.

		Protein digestibility (%)		
Food legume	Generic name	Raw	Cooked	Type of assay
Common bean (red)	*P. vulgaris*	36.3 – 56.0	71.0 – 83.0	*in vitro*
		---	62.1 – 74.1	*in vivo*
Common bean (black)	*P. vulgaris*	41.1 – 55.0	68.1 – 80.0	*in vitro*
		---	67.4 – 74.9	*in vivo*
Common bean (white)	*P. vulgaris*	42.7 – 52.0	74.9 – 91.0	*in vitro*
		---	71.7 – 78.5	*in vivo*
Cowpea	*V. unguiculata*	73.2 – 79.0	72.4 – 82.6	*in vivo*
Pigeon pea	*Cajanus cajan*	59.1	59.9	*in vivo*
Soyabean	*Glycine max*	70.1 – 82.9	85.4 – 89.7	*in vivo*
Lima bean	*P. lunatus*	34.0	51.3	*in vivo*

is due to trypsin inhibitors but even the variation in cooked samples is large and many individual values are poor; this may be due to the presence of residual antinutritional factors unless, of course, the heat treatment was less effective with some species than others.

The results of studies on human adults fed Alaska split pea (*Pisum sativum*) are shown in Table XI [25]. Feeding split peas at an equivalent nitrogen intake to that from eggs increased faecal nitrogen excretion from 0.81 to 1.16 g day^{-1}. Apparent protein digestibility for egg was 85.6%, while that for split pea protein was 78.8%. For egg protein, faecal nitrogen represents 14.5% of intake compared with 21.2% of the intake for split peas. Methionine supplementation did not change faecal nitrogen excretion (but see Table VII).

Table XI Apparent protein digestibility (%) of legume seeds in human subjects.

Legume seed and control protein	Human	Faecal Nitrogen	Protein Digestibility	Reference
Split pea	Adult	1.16 g day^{-1}	78.8%	25
Egg		0.81 g day^{-1}	85.6%	
Black beans	Children	81 mg kg^{-1} day^{-1}	64.3%	41
Milk		46 mg kg^{-1} day^{-1}	80.5%	

Additional information for children [41] is summarised in the same Table. Here, faecal nitrogen for milk was equivalent to 19% of milk nitrogen intake but for beans faecal nitrogen was equivalent to 36% of nitrogen intake. The losses of nitrogen in faeces reflect a nitrogen absorption from milk of 80.5% of intake and only 64.3% from beans.

These results from both animals [14] and humans suggest that legume seed protein is, in general, of poor digestibility.

1. *The role of the trypsin inhibitors.* It is well recognised that most, if not all, legume seeds contain trypsin inhibitors at concentrations which vary among species [12]. Since their action is to inhibit trypsin and this enzyme is actively involved in proteolysis they would be expected to interfere with protein digestibility. Raw beans have a poor protein digestibility (Table XII) but if beans are cooked properly protein digestibility is significantly increased as a result of the inactivation of the inhibitor (see also Liener, this volume). Nevertheless, even though digestibility increases after thermic treatment, it is still less than values obtained from animal proteins or even other vegetable proteins [23].

2. *The role of seed coat pigments – tannins.* Recent studies with bird-resistant sorghums show that the pigments which confer resistance also reduce the protein quality of the grains [3]. Free phenolic compounds are very common in plant materials [35] and legume seeds, particularly *Phaseolus*, are no exception; the common ones consumed are characterised by differences in the colour of the testa. Table XIII shows the protein digestibility of a

Table XII *In vitro* protein digestibility (%) in three *Phaseolus vulgaris* cultivars.

Sample	Seed Testa Colour		
	Red	Black	White
Raw			
Whole seed	36.3	41.1	42.7
Cotyledon	43.6	48.7	46.8
Cooked			
Whole seed	80.0	82.0	86.4
Cotyledon	74.0	86.0	85.9

Table XIII Protein quality (PER) and digestibility (%) of a black bean and its white-seeded mutant.

Cultivar of *P. vulgaris*	Average weight gain (g 28 $days^{-1}$)	PER	Apparent protein digestibility (%)
Black S–187 N	33	1.16	75.0
White NEP–White 2	67	1.72	83.4

white mutant (NEP–2), obtained by ^{60}Co irradiation of the black-seeded cultivar San Fernando [24]. The white-seeded mutant is more digestible than the black bean. Extensive chemical analyses which included trypsin inhibitor activity, haemagglutinin concentration, and amino acid composition show both seed types to be essentially alike. This suggests that pigments within the testa might be responsible for the differences in digestibility. If the testa contains phenols or tannins, these could well react with the protein to decrease its digestibility. The content of tannins in beans ranges from 0.34% to 0.42% in white seeds, from 0.57% to 1.15% in black ones, and from 0.95% to 1.29% in red-seeded lines. Results of other *in vivo* protein digestibility studies (Table XIV) indicate that white beans fed without the cooking broth are more digestible than either red or black beans; the latter were the least digestible of the group tested. The addition of the cooking broth to the diet decreases the protein digestibility of red and black beans but not of the white ones. Tannin concentrations were larger in the broth from red and black beans than in that from white ones and it is tentatively assumed that tannins are responsible for these effects [23]. Recently, studies on protein digestibility in humans fed on beans have been undertaken [15]. Three forms representative of the most common ways in which beans are consumed were tested: whole, ground, and strained (Table XV). Digestibility of the protein was tested when beans provided 0.6g protein kg^{-1} day^{-1}. The hypothesis was that whole beans were the least digestible and that strained beans would be most suitable; but the results show the converse to be true. We postulate that the increased surface area in strained beans favours reaction of tannins with protein, and so reduces protein digestibility in rats.

Table XIV Effect of cooking broth on protein digestibility (%) and protein quality (PER) of *Phaseolus* beans.

	Cooked beans (– cooking broth)		Cooked beans (+ cooking broth)	
	PD (%)	PER[a]	PD (%)	PER[a]
White beans	81.3	2.94	81.4	2.10
Red beans	78.7	2.93	70.4	2.10
Black beans	77.9	3.26	75.0	1.69
Casein	91.2	3.80	---	---

[a] Beans were supplemented with methionine.
Tannin concentrations in cooking broth: white: 4.6; red: 21.0; black: 10.0 μg mg^{-1}.

Table XV Apparent protein digestibility (%) in young adult human subjects fed black beans in three forms.

Type of cooked beans – preparation	Protein digestibility (%)
Whole	55 ± 4.1
Ground	58 ± 4.0
Pureed and strained	48 ± 3.8

In legume seeds there are at least four conditions which control the digestibility of the protein (Fig. 9). Evidence indicates that some species of legume foods, when raw, have a very poor protein digestibility which is caused mainly by trypsin inhibitors and haemagglutinin compounds. However, this is not a general characteristic for all species; inhibitory activity can be destroyed by heat and protein digestibility is improved. The extent of improvement depends on the method used to prepare seeds for cooking and on the control of heat in terms of temperature, pressure, and duration. These optimum conditions will vary with the age of seeds cooked and the species of legume involved.

An additional increase in protein digestibility probably results from the destruction of the tertiary structure of certain proteins, which otherwise offer resistance to enzymatic hydrolysis. This type of protein is probably a common feature of most vegetable proteins. Likewise, disintegration of cell walls may also increase digestibility.

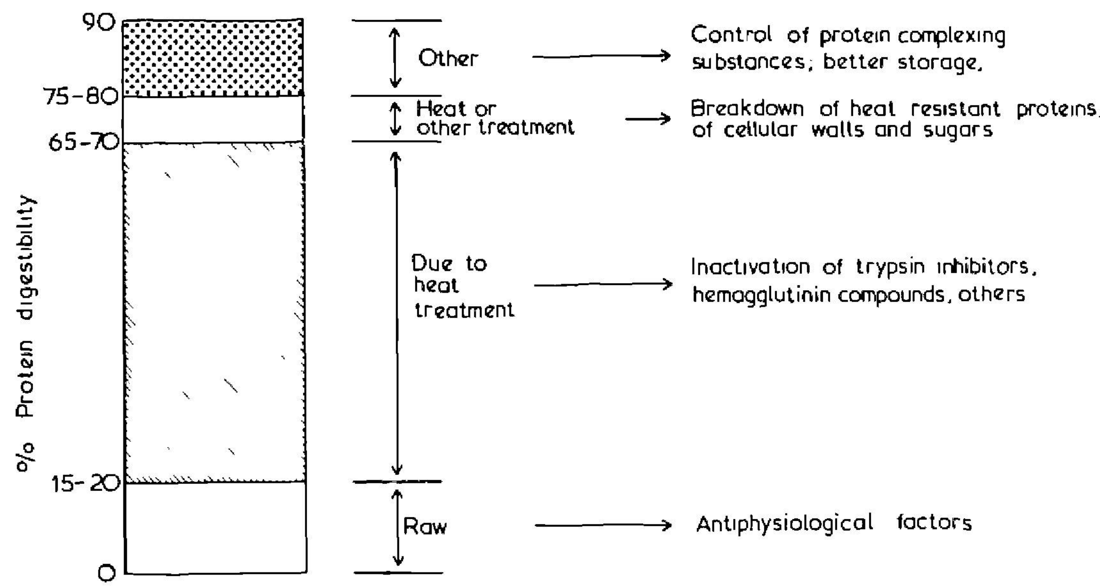

Fig. 9 Possible factors that influence the protein digestibility (%) of legume seeds.

Finally, protein digestibility can be variously improved if the effects of protein complexing substances such as tannins are minimised, controlled, or destroyed. Although we recognise that more evidence should be obtained in all aspects, particularly the last one, the evidence available shows that poor storage conditions and the colour of the seed coat, and associated presence of phenolic and, possibly, other compounds, may reduce protein digestibility and therefore amino acid availability, and so decrease the efficiency of protein utilisation.

The practical significance of an improved protein digestibility of legume seeds and of vegetable proteins is shown in Table XVI. Assuming an average

Table XVI Efficiency of land utilization in terms of the protein from beans (*Phaseolus vulgaris*).

	Protein digestibility 64%	Protein digestibility 84%
Yield of beans (kg ha^{-1})	1000	1000
Yield of protein (kg ha^{-1})	230	230
Protein absorbed (kg ha^{-1})	147	193
Protein waste (kg ha^{-1})	83	37
Waste as beans (kg ha^{-1})	360	160
Land poorly utilized (%)	36	16

yield of beans of about 1000 kg ha^{-1}, with a protein content of 23%, 1 ha of land will provide 230 kg of protein. With a protein digestibility value of 64% as obtained from human studies, as well as an improved protein digestibility figure of 84%, of the 230 kg of protein produced 147 and 193 kg will be absorbed, respectively. This means that either 83 kg or 37 kg of protein will be wasted in faeces. The wasted protein is equivalent to 360 kg and 160 kg of beans, which means that from 1 ha of land, only 640 kg of beans would be of value if the protein digestibility was 64%, compared with 840 kg when digestibility increases. If digestibility is improved, there are good possibilities of reducing protein losses in urine, through increased protein absorption. The calculation shown at the bottom of Table XVI is made on the assumption that the amino acid pattern absorbed when digestibility is 84% is the same as that when digestibility is 64%. It is certain that urine nitrogen will increase to some extent, but for present purposes it is assumed to be constant. On this basis, nitrogen retention will increase from 37 to 82 mg kg^{-1} day^{-1}: a dramatic increase in the efficiency of usage of the protein produced from 1 ha of beans. The loss of nitrogen in urine can also be reduced significantly by an increased concentration of methionine in bean protein. Therefore, to understand and solve the problem of poor protein digestibility of legume foods is of great practical importance in terms of increasing the efficiency of land utilisation for food production.

B. Effect of hardening on the nutritive value

The most evident physical deterioration in quality of legume seeds is that testas become hardened if storage conditions are inappropriate. This effect is generally evaluated by the time required to soften the beans during cooking. Apart from the undesirable culinary effects, nutritional quality could also be affected owing to the longer time required for cooking, which can destroy amino acids; or storage *per se* can affect protein digestibility as well as availability of specific amino acids. There are very few studies on these aspects but protein solubility in salt solutions, as well as the enzymatic digestibility of the protein and protein quality, all decrease during storage of soyabeans [18].

Similar results have been obtained with *Phaseolus vulgaris* [37] and further work on this problem indicates that the improved stability of short-time autoclaved beans before storage as compared with raw beans is probably due to the lack in the processed beans of conditions which permit enzymatic reactions to occur. The cooking time of common beans (*P. vulgaris*) stored for 6 months is also less affected when they are autoclaved for a short time before storage, as compared with samples not subjected to this heat treatment. It therefore seems that changes in both nutritional quality and cooking time of the seeds are related in part to enzymatic reactions which occur during conventional storage [36].

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