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Issue: *Technical Considerations for Rice Fortification in Public Health***Fortification of rice: technologies and nutrients**Georg Steiger,¹ Nadina Müller-Fischer,² Hector Cori,¹ and Béatrice Conde-Petit²¹DSM Nutritional Products AG, Kaiseraugst, Switzerland. ²Bühler AG, Uzwil, Switzerland

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This article provides a comprehensive review of the currently available technologies for vitamin and mineral rice fortification. It covers currently used technologies, such as coating, dusting, and the various extrusion technologies, with the main focus being on cold, warm, and hot extrusion technologies, including process flow, required facilities, and sizes of operation. The advantages and disadvantages of the various processing methods are covered, including a discussion on micronutrients with respect to their technical feasibility during processing, storage, washing, and various cooking methods and their physiological importance. The microstructure of fortified rice kernels and their properties, such as visual appearance, sensory perception, and the impact of different micronutrient formulations, are discussed. Finally, the article covers recommendations for quality control and provides a summary of clinical trials.

Keywords: rice fortification; technologies; nutrients; vitamins; minerals

Introduction: why rice fortification?

Rice is a rich source of macro and micronutrients in its unmilled form. During rice milling the fat and micronutrient-rich bran layers are removed to produce the commonly consumed starch-rich white rice. White rice is the number one staple food in the rice countries of southeast and northeast Asia, one of the most densely populated regions in the world. Of the world's rice production, 90% is grown and consumed in Asia. On average, 30% of calories come from rice and this can increase to more than 70% in some low-income countries.¹ In most languages of these regions, the words for rice and food are synonymous. It should be noted that rice is also an important staple food in several African countries and the Americas.

Rice is therefore a potentially excellent product for delivering micronutrients to a very large number of people and has the potential to significantly alleviate micronutrient deficiencies. However, this will only achieve the desired result as long as the sensory characteristics of the end product are not discernibly changed and people do not object to incorporating fortified rice into their daily diet. In addition, using rice to deliver micronutrients will work only as long as fortified rice is economically

accessible to people at the bottom of the income pyramid. Unpolished rice is a rich source of vitamins B1, B6, E, and niacin.² During polishing, the majority (75–90%) of these vitamins are removed. Only when parboiled does more than 50% of the water-soluble vitamin levels of brown rice remain, and this is due to their migration from the outer layers to the endosperm.²

Micronutrients: selection and suitability

It is important to stress that the selection of micronutrients depends not only on their legal status, price, expected bioavailability, stability, and sensory acceptability but also on the product forms fitting the applied fortification technology. In some applications, water-soluble forms might be suitable, and in others water insoluble or even oily forms might be preferred.

Minerals

Zinc deficiency is often an important public health issue. As in flour fortification, zinc oxide in rice fortification is doubtless the product form of choice unless a highly water-soluble product form is needed. Zinc oxide does not cause taste issues, has a good bioavailability, is cheap, and has no effect on color. There is also no effect at the levels used on vitamin A

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stability. Zinc sulphate works as well, but it is more expensive and there might be a negative effect on vitamin A stability when used together.³

Iron is considered one of the most limiting micronutrients, especially in diets based mainly on polished rice. Unpolished rice contains about 2.6 mg iron/100 grams. The native molar ratio of phytate to iron (>10) might inhibit absorption. In polished rice the iron level can be as low as 0.4–0.6 mg/100 grams.² Considering the already low bioavailability of iron in unpolished rice due to the amount of phytate,⁴ the physiological effect of the reduction of intrinsic iron from milling is expected to be low. Iron fortification and polishing of rice improves the phytate:iron ratio. Food processing, food preparation, and side dishes consumed together with fortified rice might influence bioavailability in positive and negative ways. Thus, bioavailability studies based on the active substance alone have to be considered with care. Fortification of rice with iron is only indicated if other suitable vehicles for iron fortification are not available in the food basket.

Ferric pyrophosphate is often used in rice fortification. It is nearly white or off-white, and due to its low solubility at the pH of rice, interaction with other rice components and other nutrients is low. Thus, the effect on color during storage of rice kernels is minimal. Also important is the minimal effect on the promotion of rancid fat or degradation of vitamin A. Regular ferric pyrophosphate has a mean particle size of about 20 μm and shows a relatively low interaction with the food matrix; however, the bioavailability of this grade is the lowest among the ferric pyrophosphates. Milled ferric pyrophosphate has a mean particle size of about 2–3 μm ; it has a higher bioavailability than regular ferric pyrophosphate, and it shows more interaction with the rice matrix.^{3,5} Nanoparticles of ferric pyrophosphate in an emulsifying matrix (Sunactive[®]) are not water soluble, but are reported to have a bioavailability comparable to ferrous sulphate due to the very small particle size. However, this depends heavily on the food matrix, and in rice this has proved not to be the case. It has been shown that in hot-extruded rice the relative bioavailability (RBV) of ferrous sulphate from micronized dispersible ferric pyrophosphate is only 24%. If added to rice without extrusion, the RBV is only 15%. Thus, the hot-extrusion process increases the RBV by 60%. In absolute terms the avail-

ability is only at 3%. Emulsified nanoparticles are expensive and the high cost from this formulated product might be an obstacle.⁶ In some countries, such as the United States, ferric orthophosphate is used in rice fortification, but this nearly white powder has an even lower bioavailability than ferric pyrophosphate.^{7,8}

Ferrous sulphate should only be used in special cases due to its interaction with the rice matrix. Only dried ferrous sulphate is useful and the product is limited to use in only a few technologies. It might be used in dusting and in some coating techniques; however, it can turn brown over time when converting to ferric sulphate. In addition, the water solubility of ferrous sulphate is an issue. Washing and cooking rice leads to high losses of this iron form, especially if excess water is drained after cooking. Ferrous sulphate has a metallic taste, and its taste and color effects depend on the quality of the ferrous sulphate used, even when specifications might be identical.

Iron ethylenediaminetetraacetic acid sodium salt (NaFeEDTA) became an important ingredient in cereal fortification, mainly in wheat and maize flours. Due to the high iron bioavailability in the presence of absorption inhibitors, such as phytate, NaFeEDTA would be a product form of choice in rice fortification. However, in fortification that uses nutrient-loaded rice (coating) or fortified extruded kernels with inclusion rates of about 1:50 to 1:200, there are still color issues to be solved because of the high concentration in the fortified kernels. In addition, the effect of NaFeEDTA on vitamin A stability has to be considered.

Ferrous fumarate is widely used in cereal fortification; however, in rice fortification it is not recommended because of its effects on color and taste. Elemental iron, though cheap, is also not recommended. It does not work in dusting and in extruded kernels as it leads to gray discoloration and its bioavailability is low. Other iron forms are discussed in the literature, and their suitability for rice fortification remains open.

Neither unpolished nor polished rice are rich sources of calcium. Calcium carbonate (CaCO_3) is a suitable calcium source and has a whitening effect, which might be useful in hot extrusion if more opaque kernels are needed (levels up to 30% CaCO_3 occur in fortified kernels). Hot extrusion at high mechanical energy input leads to glossy,

semi-transparent kernels that resemble parboiled kernels. Other calcium sources are calcium chloride or calcium lactate gluconate, but these are used for only special purposes. Calcium chloride has limitations due to the effect on taste. There are rice fortification techniques reported in the literature that require highly soluble forms and, in these cases, calcium lactate gluconate is recommended. However, to achieve any real fortification with calcium, large quantities of CaCO_3 in the portion are required. Considering inclusion rates of only 0.5–1% of fortified kernels (extruded or coated), the kernels will hardly have sufficient carrier capacity to supply nutritional, meaningful calcium quantities. A negative effect on iron absorption at these quantities of calcium is not likely.

Other nutrients used, for example, include selenium in the form of sodium selenite, which is used in Costa Rica.⁷

Vitamins and other nutrients

Vitamin A palmitate, stabilized with antioxidants such as butylated hydroxytoluene (BHT) and/or butylated hydroxyanisole, is the most frequently used form of vitamin A in grain fortification. Vitamin A acetate performs less well as the storage stability is not good; usually, spray-dried forms are used. In special cases, oily vitamin A forms are used, depending on the technology. Among the most frequently used micronutrients in rice fortification, vitamin A is the most sensitive. It is sensitive to light, elevated temperature, trace elements, and oxygen, as well as to low pH. The presence or absence of iron has a large effect on stability of vitamin A. Processing, washing, and cooking losses of vitamin A are moderate, though storage losses, especially at elevated temperatures, can be substantial (4–10% per month at least depending on temperature, product form, and fortification technology⁹). High-quality vitamin A has a light yellow color and has no color effect on the fortified kernels.

Vitamin E acetate can be used either as a dry preparation or a pure oily form, again depending on the technology. In contrast to vitamin A, vitamin E is very stable in its acetate form. The product is white or colorless.

Vitamins D and K are not currently used in rice fortification. However, extrapolating from the other oil-soluble vitamins, their suitability is likely.

As brown (unpolished) rice is an excellent source of thiamine and white rice is not, it was logical to consider the addition of this nutrient to white rice. Thiamine mononitrate is the form most often used. It is less soluble and less hygroscopic than thiamine hydrochloride. The use of hydrochloride makes sense only in techniques where high water solubility is needed. Depending on the fortification level, thiamine modulates taste; it is sensitive to heat above 70 °C and, accordingly, has processing losses and long-term storage losses of 30–40%.

Riboflavin and riboflavin 5-phosphate are both colorants and water-soluble vitamins. Fortification with this riboflavin is possible but leads to intensely colored kernels in cases where coating or extrusion technologies are used. Because processing losses are close to 50%, in most cases fortification with this vitamin is not done.

The following four B vitamins are highly stable during processing and storage. The first is vitamin B3, also known as vitamin PP, nicotinic acid, or niacinamide. The latter is the form of choice for fortification. Nicotinic acid is less suitable as it is a strong irritant and the handling is critical. Second, vitamin B6 is a colorless, tasteless water-soluble vitamin; the suitable application form is pyridoxine hydrochloride. Third, folic acid (vitamin B9) is a yellow/orange-colored vitamin, which is used in small quantities so as to minimize effect on color; and there is no effect on taste. For physiological reasons, it is highly recommended to apply folic acid in combination with the fourth vitamin B, vitamin B12, which is a pink-colored substance that has nearly no effect on color because of the low level in final food products, and is neutral with respect to taste. Only spray-dried forms, such as vitamin B12 1% or 0.1%, should be used, but not triturations, which have a low content uniformity.

Vitamin C, as either ascorbic acid or sodium ascorbate, is suitable for rice fortification but requires special formulation techniques. Both of the above forms may lead to a color change of the fortified kernels (to orange/light brown) but they work well in combination with β -carotene (provitamin A). The combination of β -carotene and vitamin C yields attractive orange kernels. The processing and storage losses of vitamin C are in the range of 30–50%.

β -Carotene is, at the same time, a provitamin and a colorant. It is a very stable form of a

vitamin A when protected with an antioxidant (e.g., ascorbate); however, the conversion of β -carotene to retinol depends on the vitamin A status, the amount of fat in the diet, and genetic disposition.

Rice is a good source of amino acids except for lysine, another essential nutrient of interest. By supplying additional lysine with a rice-based diet, the biological value of rice protein can be increased substantially. One option is fortifying rice with lysine hydrochloride; although highly water soluble, the majority of coextruded lysine will survive washing and cooking of rice.⁹

Technologies

Successful vitamin and mineral fortification of rice continues to be a technological challenge, in contrast to the fortification of wheat flour or maize meal, which does not cause serious issues except for the potential stability issues of low-quality vitamin A forms. The size difference between rice kernels and micronutrients is much greater than that between flour and micronutrients. Simply mixing rice kernels with a micronutrient blend will lead to micronutrient separation, inhomogeneity, and losses during production, transport, and further rice preparation, especially rice washing.

One form of intrinsic micronutrient improvement in rice, rather than fortification, was the introduction of parboiling. Before removing the bran, rice kernels are soaked, steamed, and dried again. During these steps, the content of vitamins B1, B6, and niacin in the endosperm increases three fold due to their migration from the bran into the endosperm.² In the case of high rice consumption, the total daily need of these vitamins might be covered. However, other micronutrients, such as iron and zinc, are not elevated in white rice after parboiling; this is why other means of micronutrient fortification are advisable.

Dusting

During dusting, micronutrients in the form of fine particles are blended with the bulk rice. This method makes use of the electrostatic forces between the rice surface and the micronutrients. Nevertheless, there is a segregation risk.⁷ In addition, washing and/or cooking in excess water that is then drained leads to significant losses. These losses are such that, in the United States, a warning has to be printed on the label not to rinse the rice before cooking or not

to cook in excessive water. In developing countries where intensive rice washing is practiced, dusting is not recommended.

Coating

One of the oldest ways to prevent micronutrient losses through washing is to add high concentrations of micronutrients to a fraction of the rice and to subsequently coat the rice kernels with water-resistant edible coatings, and then mix the coated kernels with normal rice in ratios ranging from 1:50 to 1:200. Most methods have in common the addition of a solution or suspension of micronutrients. Several coating layers, usually alternated with layers of coating material alone, are added by spraying the suspension through nozzles into a rotating drum containing the rice kernels to be fortified. The same drum is generally used during drying of the kernels by means of a hot air current. Many different coatings have been tried, including waxes, acids, gums (e.g., agar), starches, and cellulosic polymers (e.g., hydroxypropyl methylcellulose, ethyl cellulose, and methylcellulose^{10–12}). Except for ethyl cellulose or pectin-coated kernels, washing losses are between 20% and 60%. When cooking with an excess of water, the majority of water-soluble nutrients will be lost (60–90%).¹² The major problems encountered with coating technologies are related to color, taste, and a loss of micronutrients during washing, as well as during cooking. High variability is reported among technologies,⁷ and in many of them, consumers are easily able to distinguish the fortified kernels, which will most likely be discarded during rice cleaning. As opposed to extrusion technologies, where micronutrients are dispersed throughout the extruded kernel body, in coating the micronutrients are concentrated on the surface. The coating layer of the kernel makes them highly visible, particularly if the micronutrient forms are colored. In addition, the taste effects of the superficially present product will be high, and the resistance against mechanical separation and removal during washing low. If the coating is not resistant to cooking, it is likely that the micronutrient layer will come off leaving the vitamins more exposed to heat and moisture. Some commercially available coated rice fortification premixes claim to be stable during washing and cooking. It is advisable to stress-test these materials before incorporation into national fortification programs. Coating technologies generally imply a lower

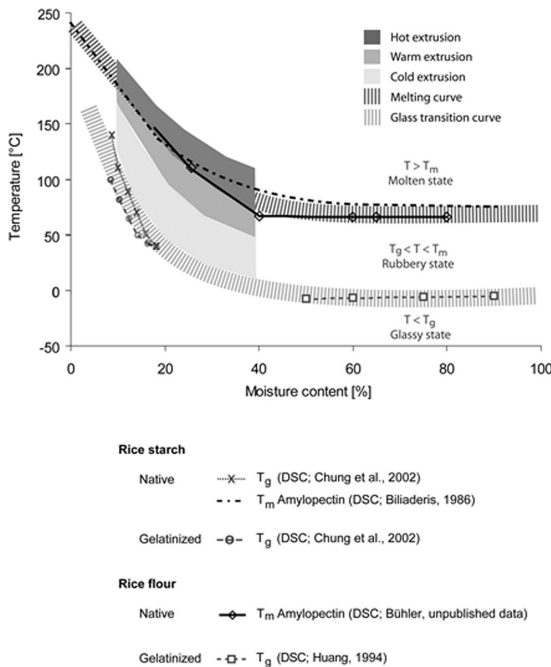


Figure 1. State of starch based on literature data and measurements taken by Bühler. Simplified interpolated glass transition and melting curves are introduced as dashed lines. The conditions during cold, warm, and hot extrusion are marked as shaded areas in the state diagram.^{34–36} SME, specific mechanical energy.

initial financial investment than extrusion technologies, but the cost per metric ton of fortified rice is relatively comparable. Coating is practiced in the United States, Costa Rica, and the Philippines.

Extrusion processing

Extruded rice kernels that carry vitamins and minerals are added in a ratio of 1:50 to 1:200 to intact rice kernels similar to vitamin/mineral-coated rice kernels. However, these kernels differ in their performance. In the food industry, extrusion is often applied where biopolymers, such as carbohydrates, are processed.¹³ Semi-crystalline polymers, such as starch, exhibit two major characteristic transitions: (1) a glass-to-rubber transition for the amorphous phase, commonly known as the glass transition temperature, T_g ; and (2) a melting of crystals at the temperature, T_m .¹⁴ Glass transition and melting temperatures depend on both temperature and moisture content and are usually represented in state diagrams (Fig. 1). Extrusion is a versatile, continuous process and uniquely combines different processing steps, such as mixing of different compo-

nents, degassing, thermal and mechanical heating, forming, and expanding.^{15–17} The process is commonly classified into cold and hot extrusion, also called *shape-forming* and *cooking extrusion*, respectively. Cold extrusion takes place at temperatures above glass transition but below starch melting temperatures, while the melting temperature of starch is exceeded in hot extrusion.^{18,19} Part of the mechanical energy input during extrusion (i.e., the part leading to a temperature increase of the product) is represented in the state diagram, while changes in microstructure and their effect on the state of starch are not accounted for. An exemplary state diagram valid for rice flour is shown in Figure 1, including processing windows for cold and hot extrusion. In addition to these commonly applied terms, we introduce *warm extrusion* as a third class, meant as an applied technological differentiation from cold and hot extrusion. Warm extrusion takes place at an intermediate temperature range that allows a partial but not full melting of amylopectin. Figure 1 shows that during cold extrusion temperature and moisture conditions allow no melting of amylopectin, and that warm extrusion allows a limited melting only, while amylopectin is melted to a large extent during hot extrusion.²⁰ The extent of amylopectin melting, also referred to as degree of starch gelatinization, in practice has a significant effect on the structural properties of rice kernels.

Cold, warm, or hot extrusion can be applied to produce recomposed rice kernels, sometimes also called *rice analogues* or simply *extruded rice*. Rice flour of different granulation plus a vitamin/mineral premix, optional additives such as binders, moisture barrier agents or emulsifiers, water, and steam are mixed to form a dough and extruded through a rice-shaped die where kernels are shaped and cut off. The rice pieces are then optionally cooked, wetted, or dusted with cross-linking agents. As a last step, kernels are dried. The different possible unit operations are shown in Figure 2. Steam is used in warm or hot extrusion only.

In cold extrusion, a pasta-type extruder is used, in which dough made from native or heat-treated rice flour, water, a vitamin/mineral premix, binders, moisture barrier agents, or other additives is shaped into rice analogues. Freshly extruded kernels are treated with setting or cross-linking agents to help retain their shape and then they are dried.²¹ The product is not heated thermally before and during

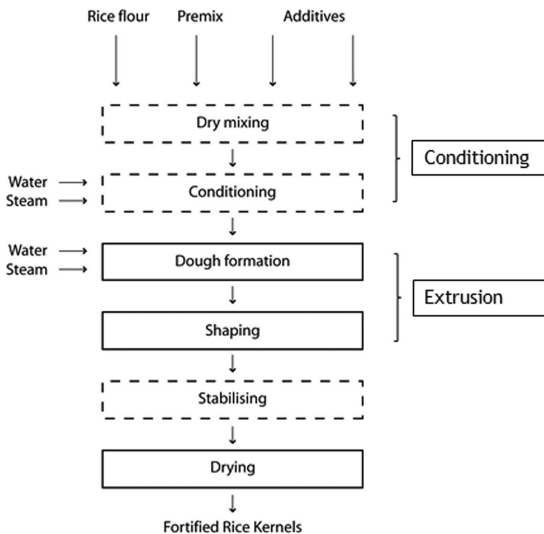


Figure 2. Different unit operations during extrusion processing of fortified rice kernels. Dashed boxes represent optional processing steps.

kernel formation; only limited heating, caused by mechanical energy input, occurs. Product temperatures are in the range of 30–40 °C, which does not result in starch gelatinization. Therefore, the addition of pregelatinized starch and binders, or subsequent boiling,²² is necessary to produce a cohesive product.

Warm extrusion can be achieved using two plant setups: (1) preconditioning with steam, followed by kernel shaping in a pasta extruder, or (2) the application of a pasta press fitted with an additional steam-injection device. The second setup was originally developed for the production of gluten-free pasta.²³ Product temperatures are between 60 °C and 90 °C in both plant setups; these temperatures, combined with low-to-moderate shear exerted in the extruder, are sufficient to achieve a partial gelatinization of the starch phase, thus structuring the product (degree of gelatinization of 60–75% in the case of a pasta press). Emulsifiers can be optionally used, but no further additives are necessary.

In hot-extrusion, dough made from rice flour, a premix, an optional emulsifier, or other additives passes through a preconditioner where water and steam are added. The dough is then extruded through twin screws cut into rice-shaped structures at the die, and subsequently dried. Temperatures at the end plate of the extruder vary between 80 °C and 110 °C. Part of the temperature increase is obtained

by preconditioning and/or heat transfer through heated barrel jackets; the other part results from energy dissipated by shear. Hot extrusion results in a high degree of gelatinization (65–85%) depending on specific mechanical energy (SME) input.²⁴ Single-screw extruders are seldom applied because conveying is inferior.²⁵

High-amylose rice flour leads to superior extrusion and end-product properties compared with low-amylose rice flour, while the use of emulsifiers restricts the swelling of starch granules.²⁶ The addition of other additives, such as modified starch, xanthan gum, and locust bean gum, were found to lead to improved hardness, cohesiveness, and stickiness of gluten-free pasta.²⁷ Mishra *et al.*²¹ describe different possible additives in detail. Moisture content during extrusion can vary between 12% and 45%. Optimal settings depend on the type of process applied and on raw material characteristics. Moisture contents that are too high leads to excessive stickiness of the dough; values that are too low lead to high mechanical friction exerted during extrusion, which results in an undesirable complete gelatinization of the product.^{23,28–30} Our own experience has shown that moisture contents between 30% and 40% lead to optimal processing and end-product properties (unpublished observations).

Independent of the type of extrusion applied, the added nutrients are embedded in the kernel matrix and are thus largely unaffected by postprocessing treatments, such as transport, storage, washing, and cooking. However, the structure of recomposed rice kernels is significantly different from natural rice kernels (Fig. 3). In natural rice kernels, nongluten protein plays a role as a structuring agent. Starch is arranged into endosperm cells within which starch granules form the disperse phase and protein forms the continuous phase. In addition, there is a distinct concentration gradient between protein and starch from the starch-rich core of the rice kernel to the protein-rich surface.³¹ After warm or hot extrusion, rice protein no longer forms networks but appears as protein assemblies distributed throughout the kernel. Starch is now the continuous phase and takes over the role of structuring agent. By optimizing the degree of gelatinization, it is possible to allow product swelling upon cooking with water while preventing excessive starch solubilization. The degree of gelatinization is influenced by both product temperature and shear during extrusion.

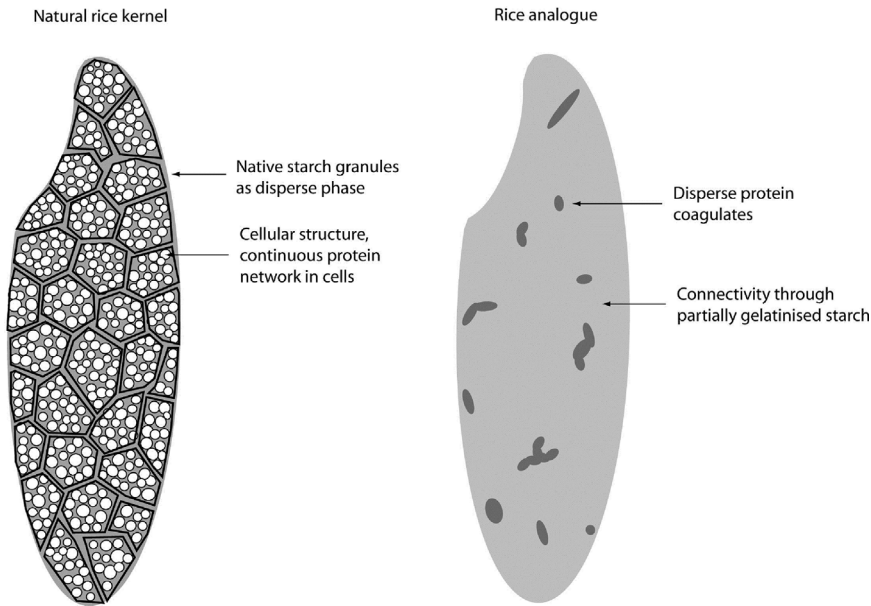


Figure 3. Schematic drawing of kernel microstructure of native and recomposed rice (not drawn to scale).

However, complex interrelationships between material, machine, and process parameters make it difficult to exactly predict end-product properties. This is why it is still common to apply the trial-and-error principle in extrusion experiments and why process functionalities are often shown as a function of the SME input only.³²

Reconstituted rice kernels by cold extrusion appear opaque, while warm-extruded kernels produced on an enhanced pasta press appear translucent and more closely resemble natural rice kernels.^{7,24} Wang *et al.*³³ showed that twin screw-extruded products exhibited superior integrity, flavor, and texture after cooking and less change after overcooking compared with cold-extruded reference products prepared on a conventional pasta press. Hot-extruded kernel appearance can be adapted well to different types of rice by modifying the choice of raw material (amylose/amylopectin ratio and granulation) and/or process parameter settings (moisture content, screw configuration/SME input). Opaque and translucent rice with smooth and rough surfaces can be obtained (Fig. 4). Cooking time, firmness, and water uptake ratio of both warm- and hot-extruded kernels is similar to natural rice, while cold extrusion leads to a softer texture.⁷ Warm and hot extrusion allows mimicking of the texture of natural rice kernels to an extent that al-

lows the addition of up to 10% of recomposed rice kernels to natural rice kernels without a perceivable change in product properties.²⁴ Figure 4 shows natural rice kernels compared with cold-, warm-, and hot-extruded recomposed rice kernels.

Comparison of various technologies

Process stability

The first challenge for micronutrients in rice fortification is the process itself to produce fortified kernels. The applied heat, the humidity during heating, the drying steps, and the presence or absence of air influence stability. In general, the process losses are between 0% and 20% in coating or extrusion technologies, depending on process, nutrient, and matrix. In dusting, the process loss itself is considered to be the smallest of all losses, as no serious stress is applied; however, segregation is an issue.⁷

Storage stability

Storage stability depends on many factors, of which the most critical is vitamin A, as compared with other nutrients it is sensitive to oxidation, especially in the presence of humidity and at elevated temperatures. The concomitant presence of iron ions enhances storage losses, even if non-water-soluble iron phosphates or pyrophosphates are applied. Rice has

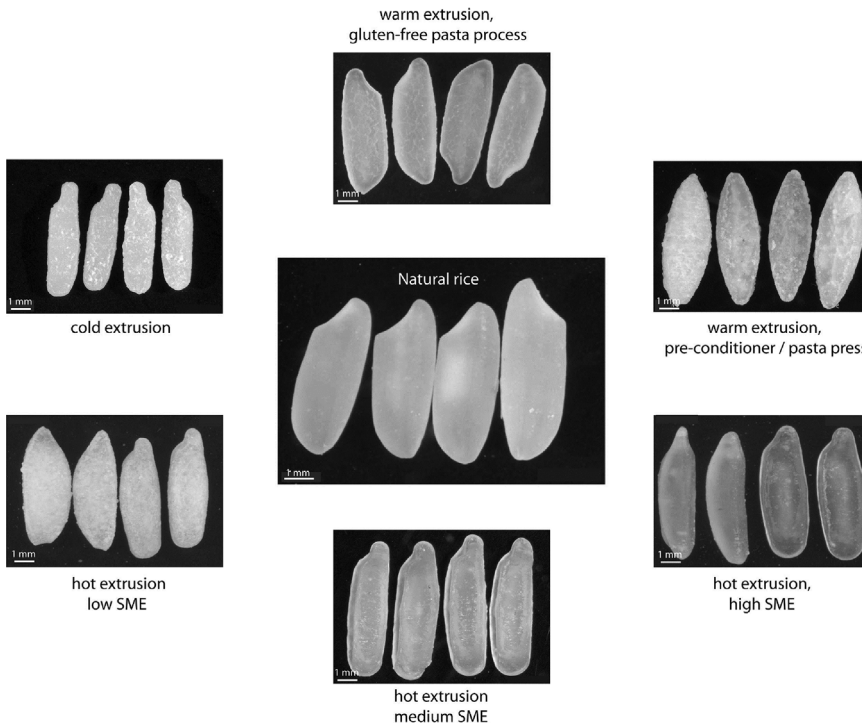


Figure 4. Visual appearance of natural rice, recomposed rice kernels produced with cold extrusion, warm-extruded kernels produced on two different types of pasta extruders, and kernels produced with one type of hot extrusion but using different screw configurations, resulting in different specific mechanical energy (SME) input.

water content of about 12.5–14%, and at a storage temperature of 30 °C the monthly losses in extruded kernels for vitamin A might be at about 4–10%. The use of an antioxidant (preferably BHT) is recommended for stabilization of this vitamin. Additional influential factors are the packaging material used and exposure to light, as well as the process used (e.g., cold, warm, and hot extrusion).³ In addition to vitamin A, vitamin B1 is heat sensitive and shows some losses. In order to guarantee a declared vitamin level, overages have to be applied, and the needed amounts have to be identified via trials. Other vitamins are shelf-stable over several months.

Washing stability

Dusting is not suitable when rice is either rinsed or soaked and rinsed before cooking. Also, most of the coated rice versions show substantial washing losses, with few exceptions, for example, when ethyl cellulose is used in the coating. Washing losses in warm- and hot-extruded kernels are very low; in cold extrusion loss depends mainly on the intensity of washing as well on the binder matrix.

Cooking stability

Dusting and coating do not allow cooking with an excess of cooking water, which is discarded after cooking. When testing different cooking methods, the lowest losses are found when rice absorbs all the cooking water (about 10–20%); only vitamin B12 losses are substantially higher (about 40%). Cooking in an excess of water that is removed after cooking results in higher losses, mainly in highly water-soluble vitamins (e.g., vitamin B12; 50–60%), whereas the losses of poorly water-soluble vitamins, such as thiamine mononitrate, is very small (about 10%). Soaking overnight and cooking the rice for 2 h leads to very high losses even for vitamin A (up to 50%) and vitamin B12.⁹

Costs

It is difficult to objectively compare the costs of the various technologies for rice fortification, as a number of factors come into play in the calculation, for example, location, prices for intact rice kernels or broken rice, electricity, steam and water cost, and plant configuration (e.g., which extruder combined

with which dryer), as well as depreciation and interest costs.

Final costs are dominated by the raw material cost, especially of the carrier used, the rice. If the technology allows the use of cheap broken rice as starting material, it is a cost advantage. This is one of the key advantages of extruded fortified kernels. Rice flour made from broken rice is the starting material. The outcome is kernels similar to intact, nonbroken rice kernels. If the market price difference between broken kernels and intact kernels offsets the production cost of extruded kernels, then extrusion will be even cheaper than dusting. Coating technologies require intact and thus more expensive rice kernels, if the coated kernels should have the form of intact rice kernels. In some cases broken rice is coated; however, broken rice is less appealing.

A further cost driver is energy cost. During extrusion, irrespective of whether it is cold, warm, or hot extrusion, water and/or steam are added, part of which has to be removed at the end of the process. The drying step is far more costly than the preconditioning step (in warm and hot extrusion) and the extrusion process itself. Drying is usually done either by using a fluid bed or pasta dryers and is energy intensive. Thus, the additional costs of fortification for rice millers might vary substantially in the range of 3–6% of the bulk rice costs.

Quality control aspects

When analyzing fortified rice, it is helpful to know which technology was applied in order to get reliable results. Dusted rice is the easiest to analyze; the added nutrients are on the surface of the rice kernels and easy to remove.

In rice fortified with either coated or extruded rice kernels there are additional challenges. First of all the micronutrients are bound on or in the carrier. This is of special importance in extruded rice, especially hot-extruded rice. The partly- or fully-gelatinized starch and the denaturated protein bind effectively with the micronutrients. Enzymatic degradation of the fortified kernels is needed before extraction.³ In addition, in already fortified rice only about 0.5–2% of kernels carry the added nutrients. The sample size has to take this into account. When an inclusion rate of 1% is used the minimum sample size that is needed for one analysis is 200 g, which corresponds to about 10,000–12,000 rice kernels. But only 100–120 kernels carry added micronutrients. This leads

to a coefficient variance of about 10% due to the few kernels in the sample, on the basis of the formula $CV\% = \frac{100}{\sqrt{N}}$. Thus, in noncooked rice the whole sample of 200 g has to be milled and mixed, and then an aliquot can be used for analysis. In cooked rice, it is necessary to homogenize the cooked soft kernels, mix the paste, and then take the aliquot.

Studies with fortified rice

Various efficacy trials have recently been conducted for hot-extruded kernels in India^{37,38} and for cold-extruded rice grains in Latin America³⁹ and Asia.⁴⁰ Significant improvement could be demonstrated for zinc⁴¹ and the added vitamins, for example B1,⁴² B12,³⁸ or A.³ Most of the studies investigating the effect of iron fortification used high amounts of iron (above 10 mg/100 g), but even intervention levels of 3 mg/100 g were able to decrease the anemia frequency, for example, in the Philippines.⁴³ In a study performed in Thailand, the negative effect of various rice phytate levels on iron absorption could be demonstrated, but also demonstrated was the iron absorption-enhancing effect of ascorbic acid-rich vegetables when added to the rice meal.⁴⁴ Various review articles and summaries give an overview of published data.^{3,7,36}

Conclusion and outlook

With respect to product properties, such as wash stability, shelf stability, cooking behavior, visual appearance, and cooked rice texture, both warm and hot extrusion can be recommended. Dusting is not a suitable technology where wash-stable fortified rice is required; and coating technologies require wash-stable coatings. Hot extrusion allows a broad adaptation of kernel properties and most closely resembles natural rice after cooking, while visual appearance of warm-extruded kernels is ideal before cooking.²⁴ Both processes lead to perfectly acceptable product properties in a 1:200 to 1:50 dilution with natural rice. From the processing side, the decision could thus be made on the basis of the type of other products manufactured in the same factory (i.e., pasta-type equipment is favorable for a pasta producer and extrusion equipment for a breakfast cereal or snack producer). To compare the bioavailability of added nutrients in the rice matrix, an in-depth study of warm- and hot-extruded

kernels made from identical ingredients is necessary in order to judge in favor of one or the other process.

The biggest challenge in rice fortification is the development of a more efficient iron fortification strategy. The bioavailability of the presently used product forms in a rice matrix is low due to the intrinsic presence of phytate. An optimal product should have high bioavailability in the presence of inhibitors and, at the same time, low reactivity with the rice matrix, which otherwise leads to color change.

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Conflicts of interest

The authors declare no conflicts of interest.

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