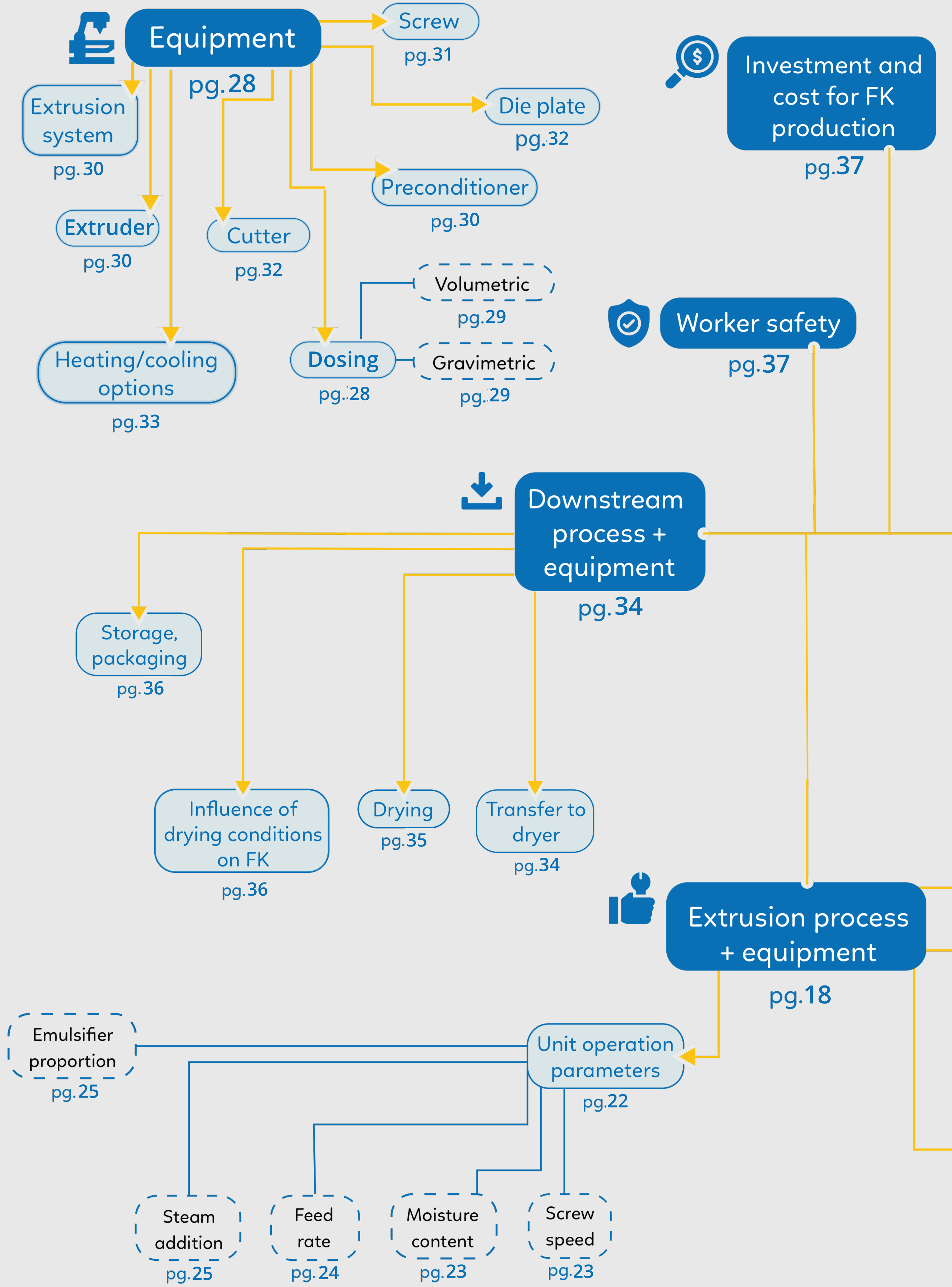
SAVING LIVES
CHANGING LIVES

Handbook for the Production of Extruded Fortified Rice Kernels

World Food Programme

gain Global Alliance for Improved Nutrition

2019



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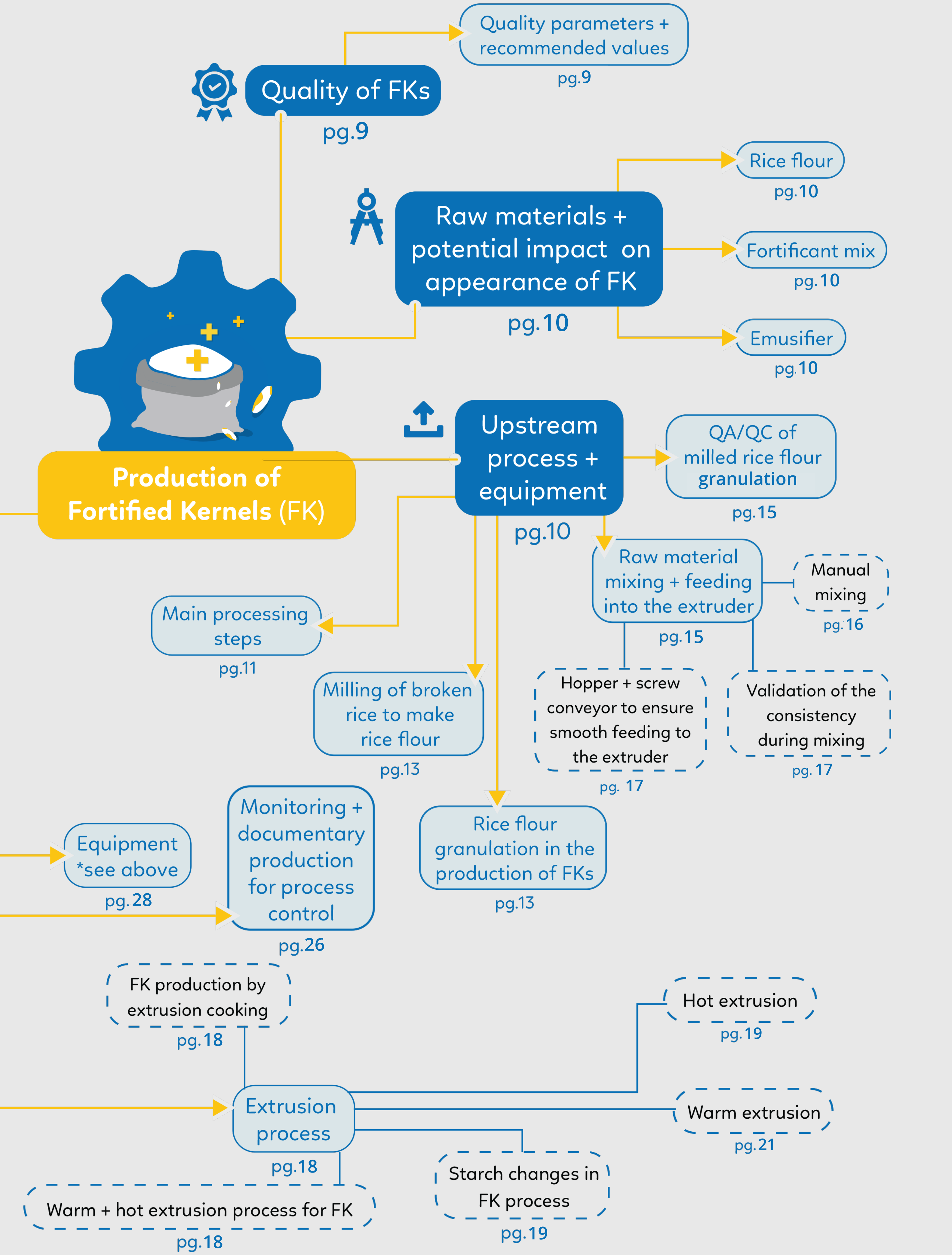
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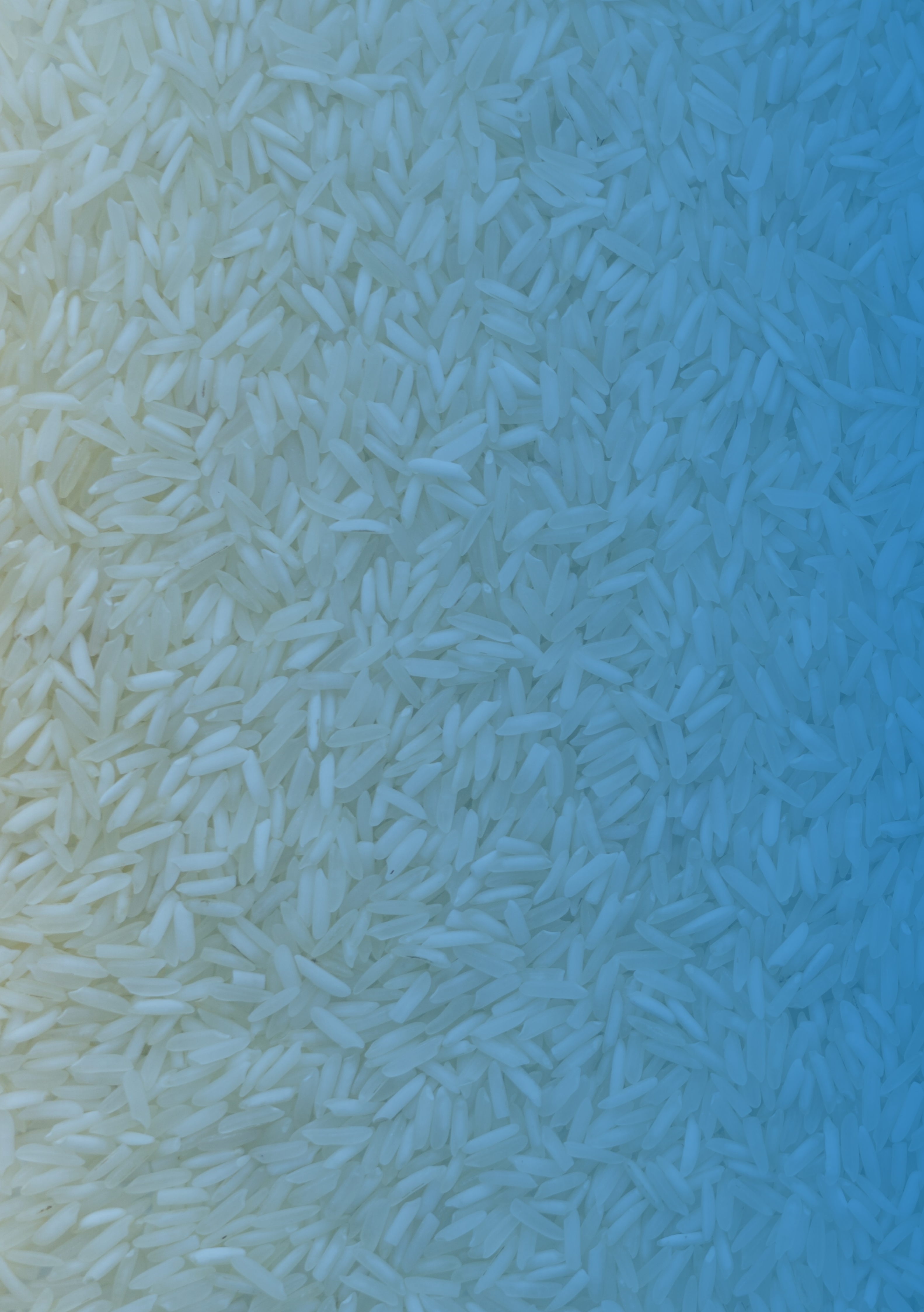

Acknowledgements

This Handbook was developed as a response to the growing interest in rice fortification using extrusion technology. Manufacturers of fortified kernels and programme personnel expressed a need to have a readily available handbook that could answer key questions related to the effects of extrusion technology on this product's fundamental quality attributes. This Handbook would not have been possible without Thomas Brümmer (Consultant), the main author; Carla Mejia (World Food Programme (WFP), Regional Bureau-Bangkok), the technical lead; and Dora Panagides (WFP, Nutrition Division) the overall project coordinator.

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Contents

1. Preface

More than two billion people are deficient in essential vitamins and minerals. Such micronutrient deficiencies are usually the result of poor quality diets, and lead to a range of disabilities including impaired brain development and cognition, impaired immunity against disease, poor pregnancy outcome, poor growth, impaired work capacity, blindness, and even death. These poor health outcomes restrict the intellectual potential of the individual, reduce the earning power of the family, and decrease the gross domestic product of the country [1,2].

One way to improve food quality in the diets of vulnerable populations is by adding vitamins and minerals to commonly consumed foods, otherwise known as food fortification. This has long-lasting positive effects on people's lives by reducing micronutrient deficiencies. Renowned scientists and Nobel laureate economists endorse food fortification as a safe, sustainable, cost-effective intervention for public health and economic development [3,4].

Rice is a staple food for over half the world's population, many of whom live in poverty. While it is a good source of energy, many nutrients are lost in the milling process which make it a poor source of essential vitamins and minerals [5]. According to the World Health Organization (WHO) Guidelines on rice fortification, "Due to its wide local consumption, acceptability, reach and quantum consumption, rice far exceeds the requirements of a staple food vehicle that can be considered for fortification purposes at a population-level intervention" [6]. With rice fortification technologies now well-established, and published studies providing evidence of the impact of rice fortification, multiple stakeholders are well-positioned to make fortified rice available through social protection programmes, as well as in the market.

This handbook was developed in response to an increasing need for guidance on the production of fortified kernels (FKs) made from rice flour, vitamins, minerals, and water using extrusion. It is meant for producers of FKs and for food science professionals supporting rice fortification programmes, as well as other interested stakeholders including regulatory monitoring technical agencies and research organisations interested in providing technical assistance in extrusion for fortification.

The overall objective of this handbook is to provide basic technical guidance on the production of FKs, using extrusion technology. It aims to address the key challenges faced in the production process and to support decision-making and troubleshooting.

It gives general details of the production process and technical requirements with the aim of decision making. It provides information on raw materials, the extrusion process, equipment, and general quality attributes of FK. This differs from previous manuals as they have focused primarily on final fortified rice. This manual is meant to guide the selection of an extrusion line for production of FKs. It is a "quick" reference and not a comprehensive manual on production. Given particularities associated with equipment manufacturers and brands, it is expected that food manufacturers will receive more specific technical support from the company from which the extrusion equipment was purchased.

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1 Horton, S., Alderman, H. and J.A Rivera. Copenhagen Consensus 2008 Challenge Paper - Hunger and Malnutrition. March 6, 2008. Copenhagen Consensus Center

2 Horton, S., 2006. The economics of food fortification. J Nutr 136 (4), 1068_1071

3 Black RE, Allen LH, Bhutta ZA et al. Maternal and Child Undernutrition Study Group. Maternal and child undernutrition: global and regional exposures and health consequences. Lancet 2008;371:243–260

4 Bhutta ZA, Das JK, Rivzi A et al. Evidence-based interventions for improvement of maternal and child nutrition: what can be done and at what cost? Lancet 2013;382:452–77

5 Champagne ET, Wood DF, Juliano BO et al. The rice grain and its gross composition. In: Champagne ET, ed. Rice: Chemistry and technology. 3rd ed St Paul, MN, USA: American Association of Cereal Chemists, 2004; pp. 77-107

6 Guideline: fortification of rice with vitamins and minerals as a public health strategy. ISBN 978-92-4-155029-1. WHO, 2018

2. Introduction

Fortification of commonly consumed staple foods is an important strategy for reducing the burden of vitamin and mineral deficiencies in a population. Multiple studies have established that, with the appropriate levels and forms of micronutrients, and with appropriate technology, fortified rice is an effective intervention to improve micronutrient status [7]. It has the potential to benefit almost half of the world's population as the majority of the more than three billion people who consume rice as their main staple are unlikely to have an adequate micronutrient intake.

Rice can be fortified with a wide variety of vitamins and minerals, including iron, zinc, and vitamins A, B_1 (thiamine), B_3 (niacin), B_6, B_9 (folic acid) and B_{12} [8,9]. Rice fortification that retains micronutrients after preparation and cooking includes a two-step process. This involves the manufacturing of FKs containing appropriate vitamins and minerals, then blending those FKs with milled rice to create fortified rice. The type of fortificants chosen, and the technology used, ensure that fortificants remain stable and bioavailable under different conditions of storage, transportation, preparation and cooking. Extrusion can produce FKs that can be blended with milled rice to produce fortified rice that is effective and acceptable to consumers in colour, taste and texture [10].

The acceptability and effectiveness of fortified rice depends on the quality of the fortification technology, the type and levels of nutrients added, and consumer preferences. Therefore, production of quality FKs is a vital aspect of rice fortification programming to ensure a positive impact on the micronutrient status of the people consuming the fortified rice.

3. Production of fortified kernels

To produce fortified kernels using extrusion, dough is made from unfortified rice flour, a mix of vitamins and minerals, water and steam. The dough is then processed through an extruder, shaped into a grain-like product that resembles rice kernels and then dried. These FKs are then mixed with milled rice at various ratios. Hot extrusion is when the extruder is set to fairly high temperatures (slightly above 100°C); warm extrusion uses temperatures between 70°C and 100°C. Cold extrusion is similar except it utilizes a simple forming extruder or pasta press which does not involve any additional thermal energy. Fortified kernels can also be produced using a rinse-resistant coating, but this document will only focus on hot and warm extrusion as they are the most widely used technologies for FK production. Moreover, no small and medium enterprises were found to be applying rinse resistant coating technology at scale.

7 de Pee S, Moretti D, Fabrizio C, Rosenzweig J. Overview of evidence and recommendations for effective large-scale rice fortification. In: Scaling up Rice fortification in West Africa. Basel: Sight and Life, 2018.

8 de Pee S, Tsang B, Zimmermann S, et al. Rice fortification. In: Mannar V, Hurrell R, eds. Food fortification in a globalized world (2018). London: Elsevier Academic Press; 2018:131–142.

9 Guideline: fortification of rice with vitamins and minerals as a public health strategy. ISBN 978-92-4-155029-1. WHO, 2018.

10 Milani P, Montgomery S, Mejia C. Introduction to Rice Fortification. In: Scaling up Rice fortification in West Africa. Basel: Sight and Life, 2018.

Conclusion

3.1. QUALITY OF FORTIFIED KERNELS

As previously discussed, FK quality depends on many factors. One important factor is the type of rice flour used, as flours behave differently during the process. Additionally, the type of equipment used has an impact on the final characteristics. Finally, the settings of the extrusion parameters are as decisive to FK quality as the raw material and equipment. It should be noted that the customer defines which quality parameters are important and which tolerances are allowed. Therefore, the expectations of the customer must be matched with the possibilities of the extrusion line.

Table 1 lists quality features that must be negotiated in detail with the rice distributor. Some of these quality parameters must be checked regularly during production on site, for example the moisture content, cooking behaviour, size and bulk density. Others, like shelf life and size distribution, are related to the equipment used.

*Table 1: **Quality parameters***

Quality parameter	Descriptor
"Rice-like appearance" and size	FK should look as much as possible like the unfortified rice that it will be blended with. Appearance varies greatly by region, and is defined in terms of length, width, diameter, whiteness and translucency. The use of national standard for milled rice is recommended as basis.
Moisture content	Moisture content should be between 10 – 14%. If the content is higher, there is a risk of mould. If the content is lower, the kernels can crack.
Micronutrient content and other ingredients	Due to losses during the energy input in the production phase and during storage [11], micronutrient content and other ingredients should be overdosed during mixing, so that their final amount in the FK meets contractual obligations. It will be difficult for most fortified kernel producers to confirm that ingredients are present in correct amounts in the end product without a certificate of analysis of the batch in question. Instead, kernel producers could provide documentation of valid quality assurance and quality control procedures, such as manual addition into the blender, and validation tests. In automated plants these procedures and tests can be checked by data collection and an alarm programmed to signal when amounts are incorrect. The test for the vitamin content should be carried out randomly by the customer or by an independent laboratory.
Shelf life	Shelf life is highly influenced by the packaging material, moisture content and degree of cooking (highly cooked starch will increase shelf life). Detailed information about FK shelf life should be obtained by the vitamin supplier. Suppliers are encouraged to do a shelf life analysis for their product through an analytical service provider capable to determine micronutrient content over time at temperatures representative of storage conditions.
Cooking behaviour	Cooking behaviour refers to the stability of the kernels during cooking. During cooking, part of the kernels may dissolve. If rice is cooked using excess water (i.e. cooking water is poured off prior to serving), these micronutrients are lost. Therefore, producers should aim for less than 10% of the FK to dissolve during cooking.
Size distribution of FK	The difference in size between the largest and smallest FK should be within the same range that naturally occurs in the rice to be blended with FKs. If this is not the case, a disaggregation can occur in the bags during transportation of fortified rice. This will cause differences in FK consumption levels.

11 Steiger et al. (2014). Fortification of rice: technologies and nutrients. Annals of the New York Academy of Sciences.

3.2. RAW MATERIALS

The main ingredient used to produce FKs is rice flour, which is usually made from broken rice, a by-product of rice milling and in some cases of parboiling. Various factors influence rice flour behaviour throughout the manufacturing process and affect the appearance of the FK:

1) Rice varieties vary greatly in protein, fat, starch content and starch composition (amount and ratio of the starch molecules amylose and amylopectin).
2) The purity of the rice flour compared to bran, other grains or components must be taken into consideration, since such products have a strong influence on the appearance of the FK. These different components influence rice flour behaviour.
3) Pre-extrusion processes, such as parboiling, affect a considerable portion of the starch content, and require significant adjustments in processing.
4) Using mixed flours (i.e. blending other grain flours with rice) could lead to deviations in FK appearance and function.

The choice of ingredients will have an impact on the final FK characteristics and processing performance and must therefore be tested. The extrusion parameters must also be adapted and validated before scale-up as part of a process controls plan.

The fortificant mix – a blend that contains selected micronutrients (also referred to as premix) – is the other main component. The type of mixture is defined in consultation with premix distributors to obtain the desired nutritional content with the minimal changes in the FK final appearance. Additionally, some countries have a national standard for fortified rice, which will set the requirements for the micronutrient quantities needed in the fortificant mix. The nutrients included in the fortificant mix may have affect the appearance of the FK due to the type and level of added vitamins and minerals. For example, the type of iron used in a premix could lead to changes in appearance that vary from neutral to light grey or rust-like brown. The addition of riboflavin may produce a yellow FK. In some cases, fortificant mixes also include flowing agents added to improve the mixing abilities of individual components and prevent clumping. However, in the case of fortified kernels production, these can negatively influence the extrusion process and should be discussed and revised with the premix supplier. For example, dextrins – which increase the stickiness of the premix when steam or hot water are applied – should be avoided. A good alternative flow agent is fine rice flour.

In addition to rice flour and fortificant mix as the most basic ingredients, an emulsifier can optionally be used to influence the processing properties of rice flour. An emulsifier can change the dough texture, reduce its adhesiveness and could help retain final product shape after hydration or cooking. The most commonly used emulsifiers are mono- and/or diglycerides of fatty acids. However, any emulsifier should be tested throughout the process to choose the best functional and cost-effective option.

3.3. UPSTREAM PROCESS AND EQUIPMENT

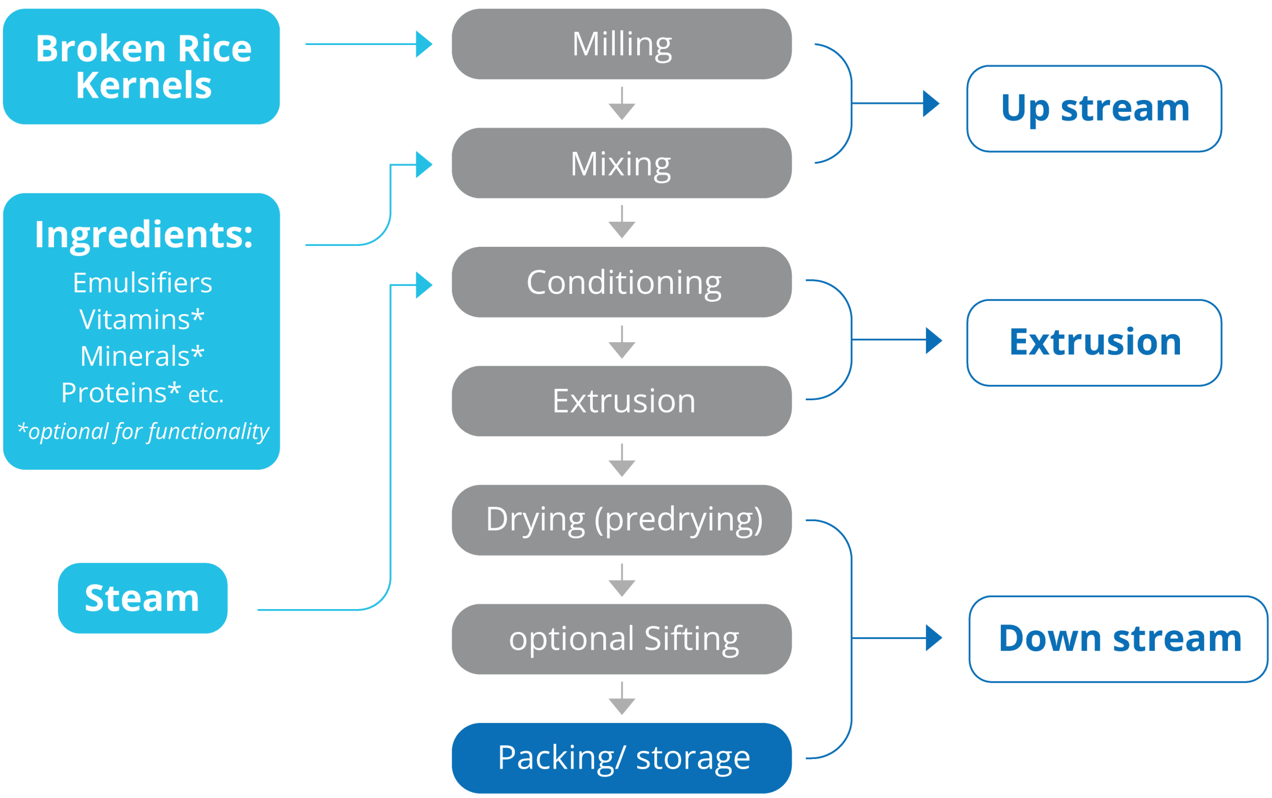
Before the extrusion begins, several components must be in place to ensure sufficient, clean and homogeneous raw material with the desired formulation for continuous, reliable production of FK. This is called upstream process. When designing these components in the processing line, the installed capacity of each individual section should be greater than the capacity in the following section, or the next part of the upstream process. For example, the capacity of the rice flour mill should be greater than the capacity from the extrusion process. The final output determines the capacity of the line and thus it is quite important to discuss the individual outputs with the equipment manufacturer. Moreover, transportation between the individual operating units in a production plant (on one floor or several floors) should utilize gravity wherever possible. Alternatively, pneumatic transports, spiral screws, elevators, or conveyor belts can be used. Only in plants with a low degree of automation should manual transport be considered.

Processes to handle raw materials need to be in place before the extrusion system begins. The main raw materials are rice flour, the premix, and emulsifier. Polished rice must be ground to a fine flour before mixing with the other ingredients. Hence, it is most cost effective if the process starts with procurement of broken rice directly from a rice mill.

Figure 1 [12] summarizes the main processing steps of FK production using hot and warm extrusion.

12 Adapted from Bühler, A G

Figure 1: ***FK production process***



If the process starts with paddy rice, then all process unit operations normally used for rice milling need to be integrated before grinding the rice into flour. Figure 2 [13] shows a diagram of an upstream process for rice flour cleaning, milling, sifting and storage before FK production.

13 Source – Wenger Inc., published and unpublished material.

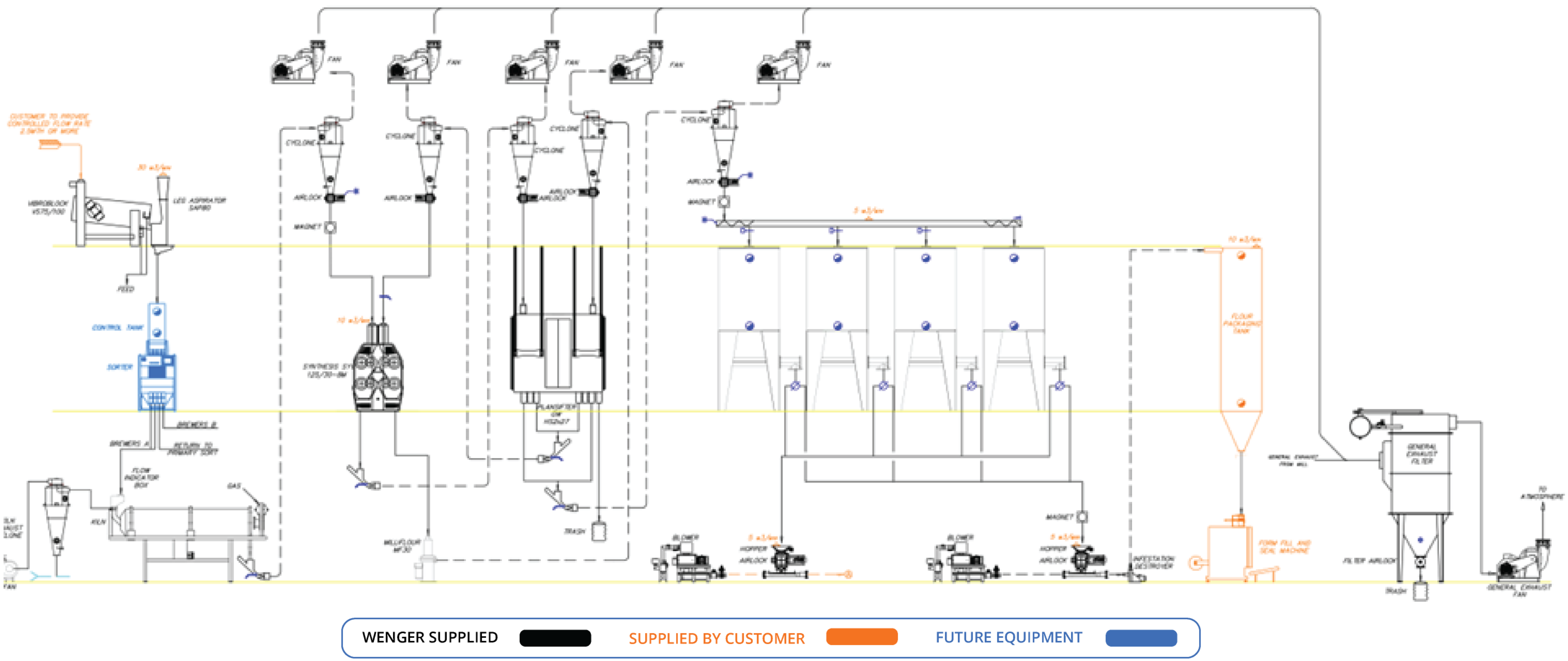


Figure 2: ***Schematic overview of optional upstream components as an integrated process line for production of rice flour***

MILLING OF BROKEN RICE

A fine homogeneous rice flour (100% <50-70mesh or <300µm particle size) will give the best result for FK appearance. Processing capacity can also be increased by using fine rice flour. Of the many types of mills on the market, a hammer mill produces optimum results for continuous cost-effective production. The sieve in a hammer mill determines the granulation of the flour. Such mills can be designed considering the mesh size of the screen, the open area of the screen and the installed engine power. The equipment supplier must guarantee that the supplied parameters match the desired granulation of the rice flour.

Figure 3 [14,15], shows mills with various capacities. The expected capacity of the rice flour mill should be at least twice that of the subsequent extrusion process, so that the supply of rice flour does not represent a bottleneck for the more complex and continuous extrusion process.

To make rice flour, whole or broken polished rice is usually fed with a screw conveyor or pneumatic transport to the mill. The speed of the conveyor (screw or pneumatic) determines the amount of rice grains that are conveyed into the grinding chamber. In an automated production line, the conveying speed is optimized by monitoring the mill's energy consumption.

If broken rice is procured externally, a detector and/or separator for magnetic and non-magnetic metals should be installed in front of the mill to avoid damage, and to prevent or control mechanical hazards. When the flour is pneumatically transported behind the hammer mill, this installation, in accordance with national and regional regulations, should be provided with explosion protection devices (e.g., rupture disks and spark detectors). This also applies to all other pneumatic transport devices for powdery materials in the system. Manual operation of the mill requires dust protection.

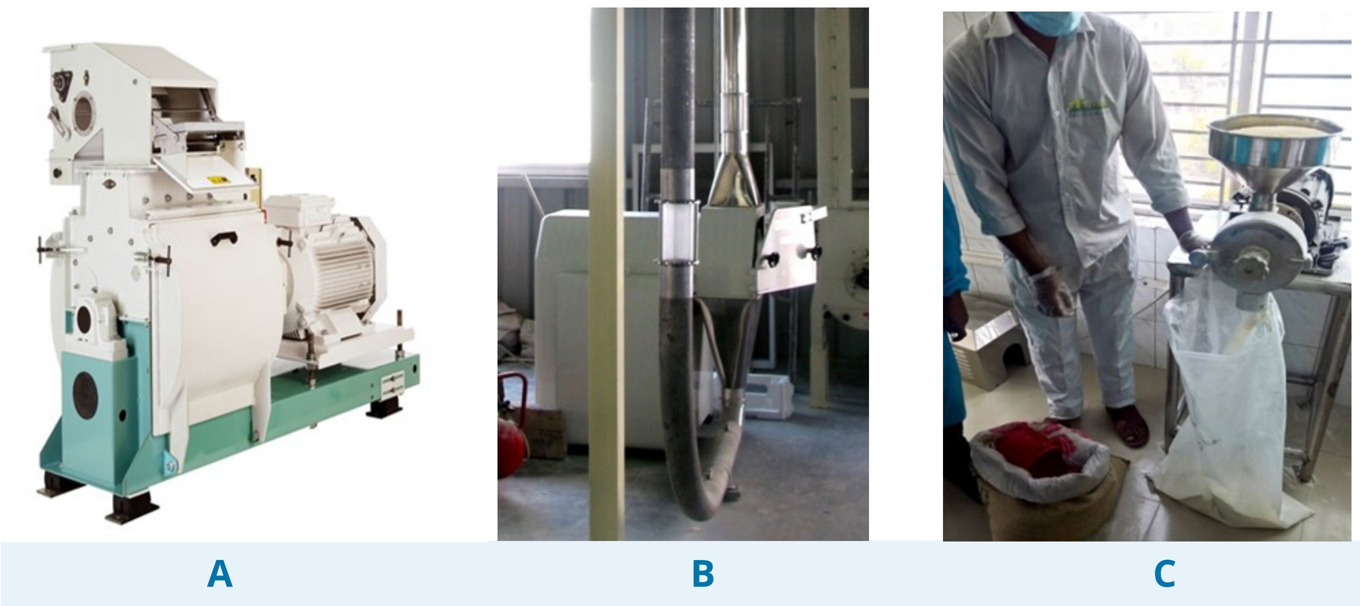


*Figure 3: **Different types of mills. A)** Hammermill with up to 2000kg/h ; **B)** Hammermill with up to 300kg/h in automated production; **C)** Small Diskmill with manual operation*

RICE FLOUR GRANULATION IN THE PRODUCTION OF FORTIFIED KERNELS

The milling process of rice flour is very important for the entire production of FK. The granulation of flour influences different aspects of the process. Although grinding a very fine flour means greater investment and a higher use of energy, it also brings decisive advantages that improve FK quality. The finer the flour granulation, the lower the energy requirement for the production of a homogeneous dough in the preconditioning and extrusion processes.

In addition, flour granulation affects final product appearance. Figure 4 [16,17], shows photographs and microscopic images of FKs produced under the same extrusion conditions using flour with different granulation. In product A, made with more coarse flour (>300µm), particles are still visible on the FK surface. The corresponding microscopic figure shows that a few areas have remained white, suggesting under cooking and a lack of disintegrated particles. This represents a significant reduction in quality compared to product B, made with a fine rice flour, which shows a much smoother surface, without visibly uncooked regions.

14 Figure 3 Picture A from Bühler - https://www.buhlergroup.com/global/en/products.htm
15 Figure 3 B, C: Picture by Dr T Brümmer
16 Pictures of FKs - Dr. T. Brümmer: unpublished material.
17 Microscopic pictures – Bühler AG, published and unpublished material.

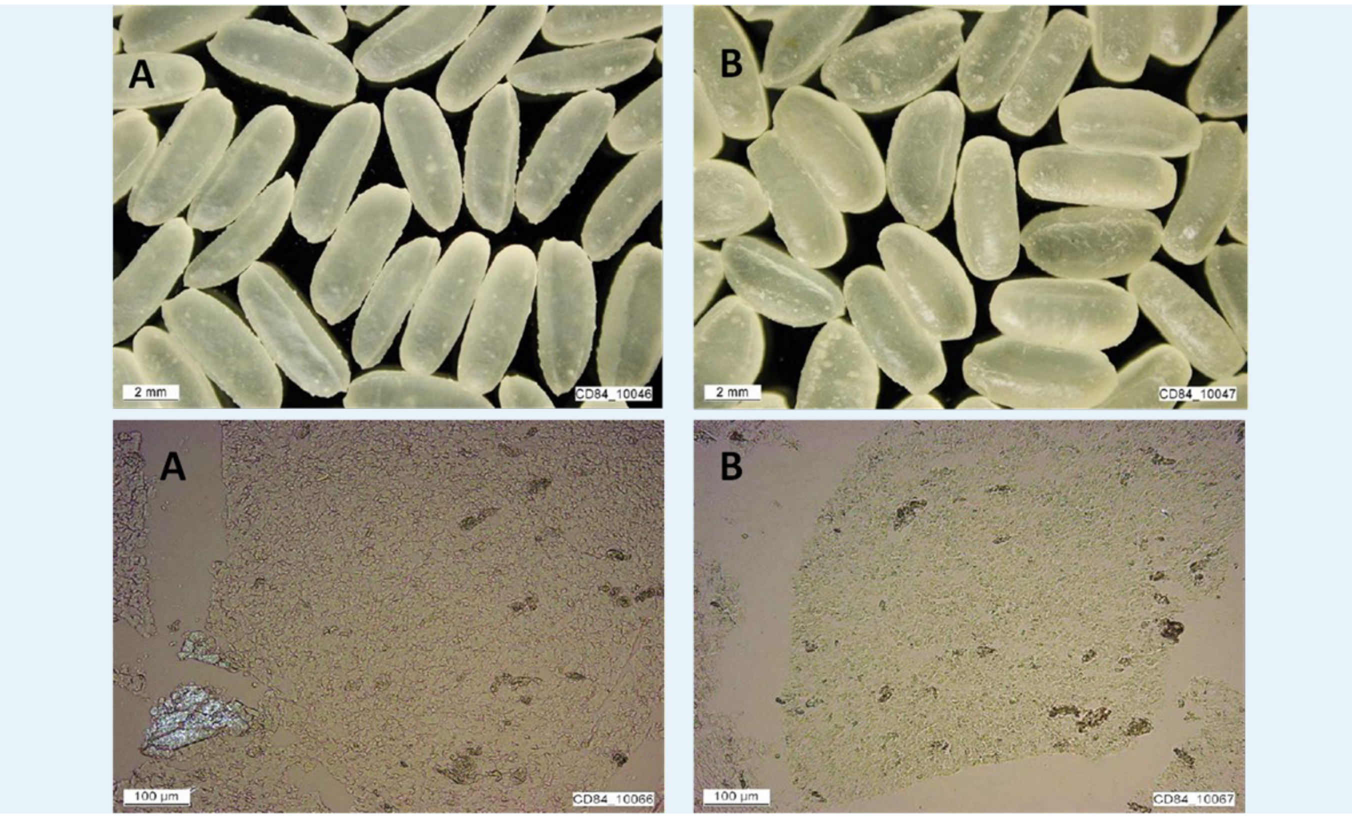
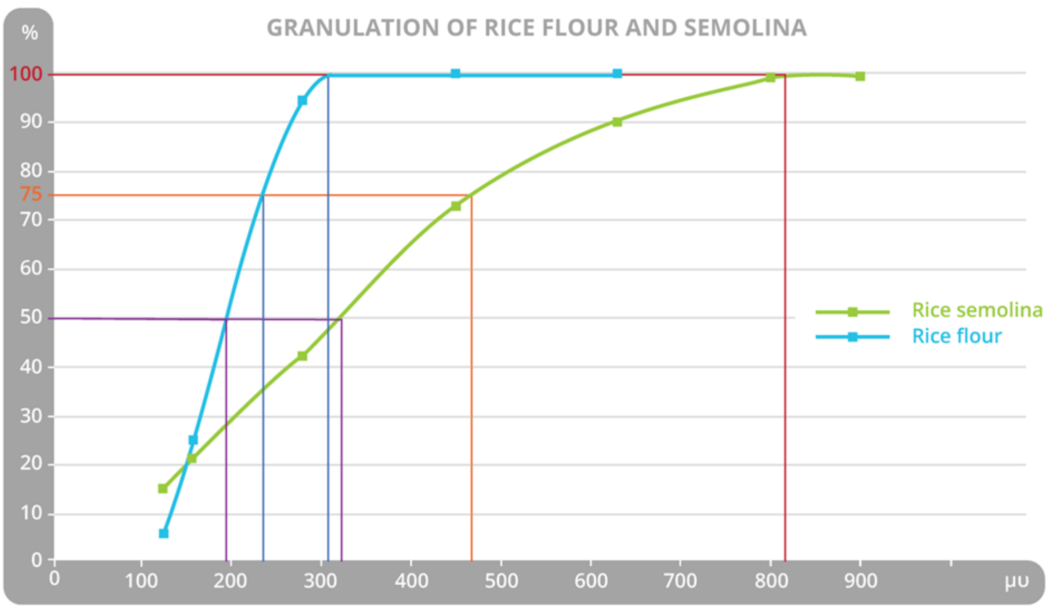


Figure 4: ***Influence of raw material granulation on FK; A)*** *photo and microscopic photo of FK from rice semolina;* ***B)*** *photo and microscopic photo of FK from fine rice flour*

To determine grinding quality, the flour can be sifted with different sieve grades. The quantities of the individual fractions obtained after sieving are then weighed and displayed as a fraction curve or cumulative curve to highlight the differences of different powders. For example, Figure 5 [18] shows the granulation curves for rice flour and rice semolina, in which rice flour presents 50% of its particles with 200µm or less. In the case of semolina, only about 28% of the particles are 200µm or less, and 50% are <320µm. In general, a finer particle size (100% <50-70mesh or <300µm) will result in better dough and product characteristics.

Figure 5: ***Granulation curves of flour and semolina from broken rice***

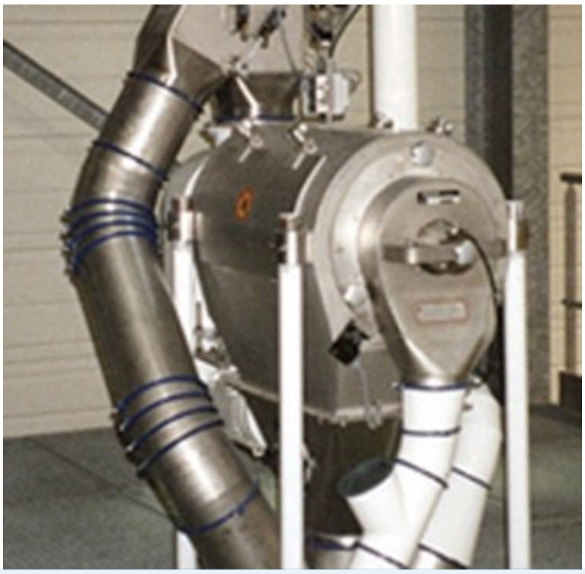


18 Adapted from Dr. T. Brümmer: unpublished material

QUALITY ASSURANCE AND CONTROL OF MILLED RICE FLOUR GRANULATION

A fine homogeneous rice flour (<300µm) will give the best FK appearance. Thus, grinding and sieving impact the granulation or particle size of the flour, which in turn affects FK quality, and require regular control. In mills with integrated sieves, this function is automated. In the case of a defect of the filter sieve, for example a tear, the control panel shows an increased coarse fraction, which affects negatively the quality of the grinding and thus, the rice flour. So, if the control panel shows an increased coarse fraction, measures must be taken to repair the filter sieves.

If mills do not have an integrated sieve, then flour sifting should be done manually to separate flour with the desired granulation from coarser particles. Coarse particles can be returned to the mill for further grinding or used for other products. The sifter may be a plansifter that vibrates, or it could be a rotating drum screen. With a plansifter, different fractions of flour can be separated, while a rotating drum sieve results in only two fractions. Figure 6 [19,20], shows two options for sifters.



A

B

*Figure 6: **A)** Inline control sifter with a rotating drum screen; **B)** small size plansifter with different screens*

RAW MATERIAL MIXING AND FEEDING INTO THE EXTRUDER

Mixing

The production of FKs requires that all raw material components must be processed in exact proportion to each other. The raw material recipe must always be fed into the FK process in the correct amount. This can be achieved by mixing the components before the FK manufacturing process. Another option is to install separate continuous feeders for each ingredient.

Due to lower costs, premixing raw materials is usually preferred. Paddle mixers are efficient in premixing (see Figure 7 [21]). The mixing chamber is filled in batches – either automatically or manually – or with a combination technique whereby the main component (the rice flour) is automatically added, and additional ingredients (fortificant mix, emulsifiers if used) are incorporated manually. Automation has the advantage that the weight of each component can be documented in every batch. The mixer is the most important unit in ensuring an even distribution of the ingredients with the flour.

19 Picture A, Adapted from Dr T Brümmer
20 Picture B, Adapted from http://www.chinafoodmachinery.cn/index.php/Product/viewequ/id/169.html
21 Adapted from Pictures by A.G. Bühler

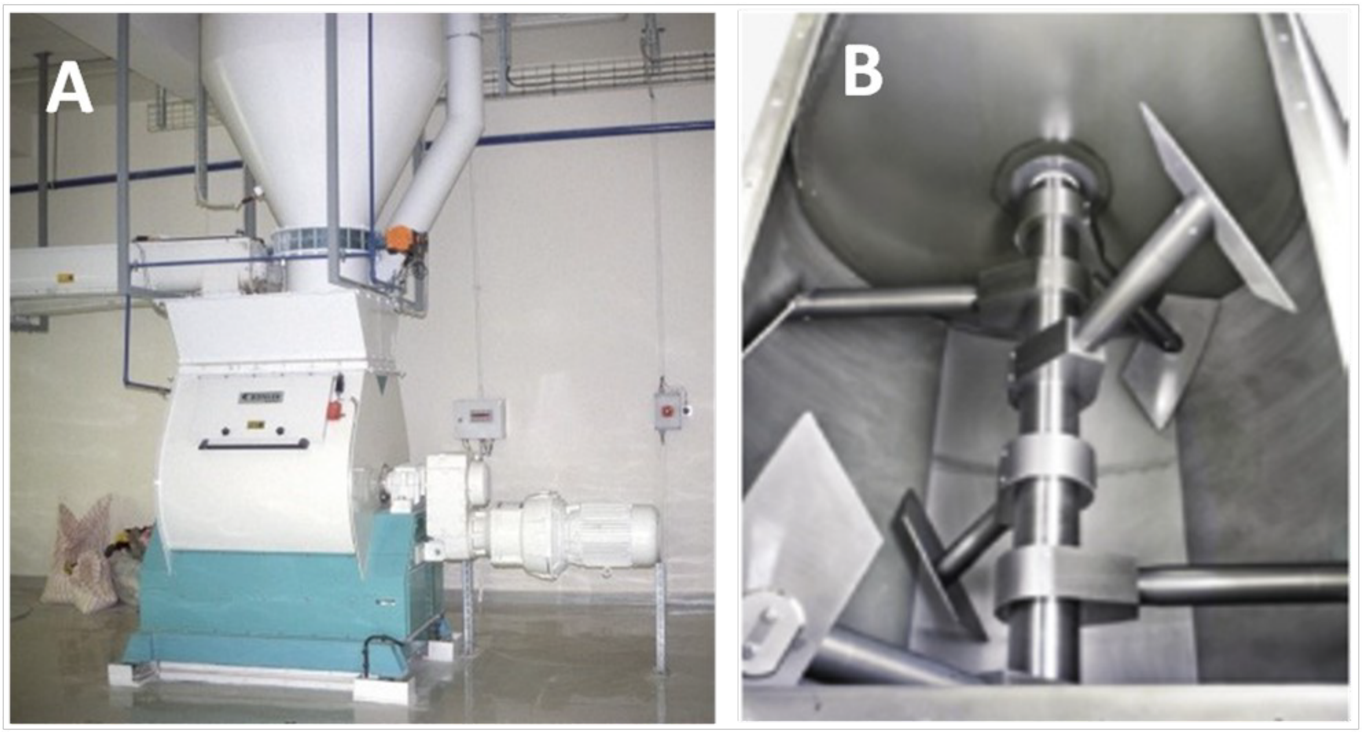


*Figure 7: **A)** Paddle mixer on weigh cells for automated production; **B)** Inside view into a paddle mixer*

MANUAL MIXING

Vertical batch mixers are usually used in warm extrusion lines (see Figure 8 [22]). Hot water (~90°C) is added to the flour and micronutrient premix in an excess of up to 33% and mixed until the ingredients are homogeneously distributed (at least 10 minutes according to one processor interviewed) to simulate pre-cooking inside the preconditioner. Screw conveyors transfer the prepared mixture into the hopper and then the extruder.

*Figure 8: **Vertical mixer with a volume for ~ 25kg batches***

22 Pictures by Dr T Brümmer Milani P, Montgomery S, Mejia C. Introduction to Rice Fortification. In: Scaling up Rice fortification in West Africa. Basel: Sight and Life, 2018.

If the mixer is filled manually, it is important that all ingredients are added in correct amounts as per the required formulation. This should be monitored and documented. Manual mixers must be operated very carefully due to open access to the mixing chamber's high-speed rotor blades, which can be hazardous. The use of covers, safety switches and warnings are recommended. Insulation of the screw conveyor and hopper, as well as a cover, also helps maintain temperature control while the dough is being moved to the extruder, which improves the effect of hot water addition to the starch.

With manual mixers, the mixer's volume and its processing time for a batch must be adapted and optimized to the desired extrusion throughput. For example, if the ideal mixing time recommended by the equipment manufacturer is 10 minutes, then the time needed to input the raw materials and the time to transfer the mixture into the hopper for dosing needs to be added, which makes a total of ~ 15 minutes per batch, or four batches per hour. If the extruder has a 400 kg/h throughput, the mixer needs a volume for a minimum of 100kg fortified kernel dough for each batch.

Due to high humidity in FK production, all equipment (especially the augers) should be cleaned carefully and frequently to prevent mould growth.

VALIDATION OF THE CONSISTENCY DURING MIXING

The mixing process used for the preparation of the dough should be validated for quality. For this purpose, the mixing process should be carried out according to the standard recipe, with the specified fill level and according to the equipment manufacturer's designated optimal mixing time. From the finished batch, at least ten samples should be taken from different points in the mixer. Of these samples, at least one nutrient out of the micronutrient premix is then analysed by an independent laboratory. This nutrient should be present in amounts that do not differ too greatly from the specification (10-15%). Using the results of these analytics, a coefficient of variation (CV%) can be calculated. WFP's online calculator [23] can facilitate this estimate.

A mixer may be considered as validated if the coefficient of variation is no larger than 10% (i.e. +/- 10% around the average). This validation only applies to this operating point; with significant changes to the recipe or standard operation, this test must be repeated.

The capacity of the mixer and the time to complete a batch must be matched to the extrusion capacity. Ideally, the mixer has twice the output required by the extrusion process to ensure that there is always an adequate amount of mixed raw material available.

HOPPER AND SCREW CONVEYOR TO ENSURE SMOOTH FEEDING TO THE EXTRUDER

When the mixture of rice flour, fortificant mix, emulsifier, etc. is ready for use, it is conveyed from the mixer into a storage container called a hopper for the next stage of FK processing. Therefore, rapid emptying of the mixer is important. Most mixers have a large opening at the bottom of the mixing chamber to achieve rapid emptying and ensure the mixer is ready for the next batch.

The hopper under the mixer should be equipped with a screw conveyor. The screw conveyor moves the correct amount of mixture from the hopper to the extrusion process. From this point onwards, it will be a continuous process. To minimize refill time, the screw conveyor should have a very high capacity (kg/min), at least 15 times the capacity of the extrusion process that varies depending of equipment manufacturer and brand. A short refill time is of great importance, especially when using gravimetric dosing in the extrusion process, as dosing switches to volumetric running during refilling (**see Dosing on page 28**).

For raw materials of procured externally, it is recommended that an additional sifter and a metal detector and/or separator are placed directly in front of the mixer, or in front of the extrusion system, to obtain a safe and metal-free raw material mixture for the extrusion process. In the case of automated process-controlled operations, level sensors in the hoppers provide the signals for refilling the hopper or for starting a new mixture.

23 WFP Online Calculator (29.01.2019): http://foodqualityandsafety.wfp.org/en/coefficient-of-variation-calculator

3.4. EXTRUSION PROCESS AND EQUIPMENT

EXTRUSION PROCESS

In extrusion cooking, raw materials are mixed, compressed into a dough, and finally shaped. The technology is based on a screw system which compresses the dough within a tube or barrel, heats it, and then pushes it through small openings called die holes (see Figure 26, page 38). These rice-shaped die holes are the first step in shaping the fortified kernel dough into a shape resembling milled rice grains. When leaving the die hole, strands of dough are cut into individual kernels by rotating knives. The rotational speed of the blades, together with the dimensions of the die holes and the throughput per die hole, define the thickness of the FKs. The high temperature causes changes in the structure of components such as starch (gelatinization) and protein (denaturation). FKs produced in this way must be transferred to the downstream process for drying.

An extrusion cooking process has various key features: the device through which raw materials are fed, the design of the screw system and its barrel, the dimensions and number of holes in the die, and the cutter and conveyor that moves the extrudate further.

During extrusion, raw materials are fed in at a constant rate, while the machinery maintains a steady-state equilibrium. This is achieved by balancing the forward flow produced by the screws against the pressure at the die. It is a process contingent upon the independent variables of the equipment, raw materials and extrudates, meaning that one of these variables may affect several product characteristics [24].

FK PRODUCTION BY EXTRUSION COOKING

To produce FKs by extrusion, fortified flour is converted into dough using a rotating screw. This requires energy, which increases the temperature of the dough. This limits the capacity of the FK process, as the dough at the outlet of the die plate must not be allowed to expand. Such expansion occurs when the temperature of the water in the dough is so high (~100°C) that the pressure difference at the exit point converts the liquid water into steam. Steam has a higher volume than liquid water and so causes the dough to expand. While expansion is desired for some puffed products (e.g. breakfast cereals, snacks), it must be avoided in case of FK.

The conversion of the starch particles in the four into an amorphous dough requires a certain energy input, which depends on the degree of preconditioning and the granulation of the flour. A very fine flour (100% <50-70mesh or <300µm) and an optimal preconditioning reduce the amount of energy needed to produce a good FK. This energy reduction results in a lower temperature of the mass in the extruder. Thus, the process capacity can be increased if the energy input is high enough to produce an FK with a good appearance, but the temperature is low enough to prevent expansion.

Warm and hot extrusion process for FKs

The terms warm and hot extrusion are used to differentiate the extrusion lines' characteristics that affect the process and, subsequently, the product quality. Regardless of the process, **FKs are of optimal characteristics if all starch granules are fully gelatinized**. This occurs only if the dough is completely cooked. Rice flour that is not cooked thoroughly by the extrusion process results in partly gelatinized starch granules. As a result, FKs disintegrate during cooking by the consumer, which will cause micronutrient loss if rice is cooked in excess water.

In hot extrusion, the dough in the extruder reaches temperatures slightly above 100°C. This gives flexibility to modify ingredients such as rice flour to improve processing capacities and end-product properties. FK production by means of hot extrusion was jointly patented in 2005 by DSM IP Assets B.V. (DSM) and Bühler AG [25,26]. The patent describes the production of FK in detail using twin-screw hot extrusion with a preconditioning step with the addition of steam and drying process. Together with the actual extrusion process, these steps are decisive in the production of a high-quality FK.

In the warm extrusion process, the temperature of the dough in the extruder should never exceed 100°C. Warm extrusion systems have some deviations from the method described in the patent despite their similar production systems. Most of the descriptions of warm extrusion lines in this document are related to observations of two lines operating in Asia (Warm Extrusion A and Warm Extrusion B, or WE-A and WE-B), which are representative examples of these systems.

24 EXTRUSION COOKING / Principles and Practice, R C E Guy, Campden & Chorleywood Food Research Association, Chipping Campden, UK, Copyright 2003, Elsevier Science Ltd

25 Patent: WO2005053433 24.01.2019: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2005053433&tab=PCTBIBLIO&maxRec=1000

26 Dr T Brümmer, one of the authors of this publication, is an author in this patent. However, he obtains no financial or other benefits from this patent, and has contributed to this Handbook freely and independently.

Starch changes in the FK process

The desired rice-like appearance in FKs is achieved by processing rice flour with enough water, heat and shear. The starch in the flour, as the main and most important structural component in the FK, should be cooked and forced so that most of the starch granules are fully gelatinized and dissolved into a homogeneous mass. Such a mass gives the desired matrix for the vitamins and minerals.

Figure 9 [27] shows the changes that the starch undergoes in the hot extrusion process. During preconditioning, starch can gelatinize by absorbing water at temperatures above the gelatinization temperature, but the granular shape remains. The necessary dissolution of the granular shape takes place in the extruder by introducing shear energy via the screw elements. If temperatures are exceeded, the dough needs sufficient cooling at the end of the extruder to prevent expansion. To achieve this, venting and cooling of the last extruder section can be used.

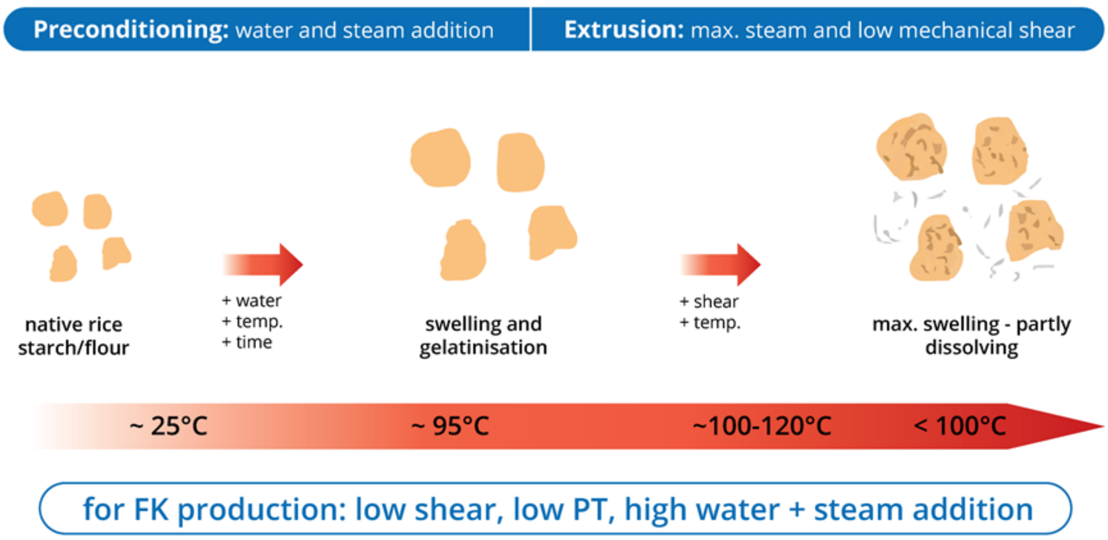


Figure 9: ***Schematic description of starch transition in the hot extrusion process***

Hot extrusion

Figure 10 [28] shows a schematic description of the FK hot extrusion process, including the temperature of the dough, water content, pressure and the degree of filling during the process.

Preconditioning, usually observed only in hot extrusion lines, prepares the flour, subjecting it to steam so that the extruder can convert it into a cooked dense mass with minimal energy input. During the preconditioning step, it is possible to vent or degas the process chamber by vacuum suctioning. This option is especially useful if the raw material is not very fine. A coarser material needs more shear to get a good surface appearance. More shear, however, leads to higher temperatures. Venting removes a significant amount of water in the form of steam from the dough inside the extruder. When using a vacuum, this effect is further enhanced. The removal of water and steam simultaneously causes the mass to be significantly cooled. The investment in degassing is therefore very worthwhile if high throughputs from the extrusion process are needed.

27 Adapted from Dr. T. Brümmer: unpublished material
28 Adapted from Dr. T. Brümmer: unpublished material

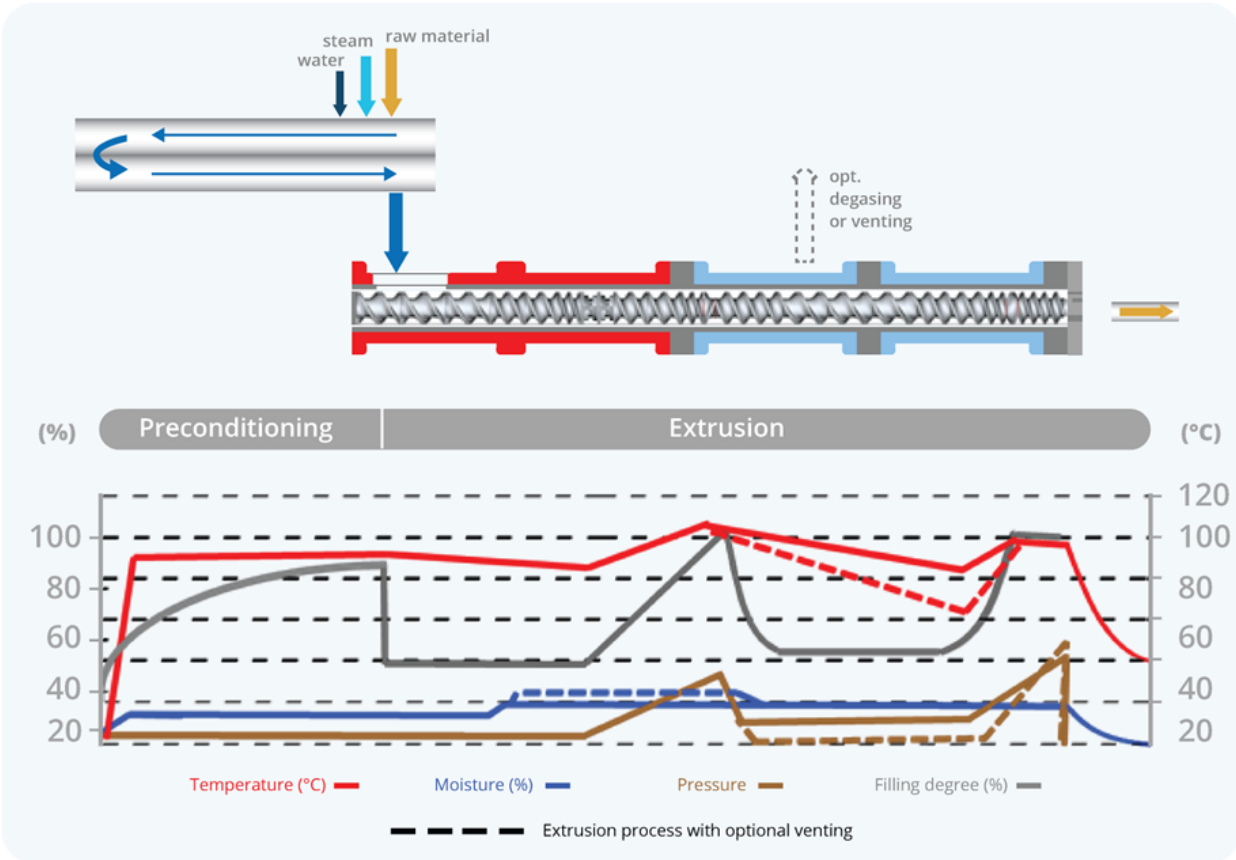


Figure 10: ***Schematic description of the FK hot extrusion process including the preconditioning step***

The following figures are examples of hot extrusion equipment used for FK manufacture. Figures 11 [29] and 12 [30] show extruders with preconditioners for 300-400kg/h and up to 500kg/h FK production; Figure 12 shows a dosing system for two powder components, such as rice flour and vitamin/mineral premix.

Figure 11: ***Twin screw extruder for FK - Bühler AG - BCTG62 – 300-400 kg/h FK***

29 Picture by A.G. Bühler

30 Pictures left to right Wenger and Dr. T. Brümmer

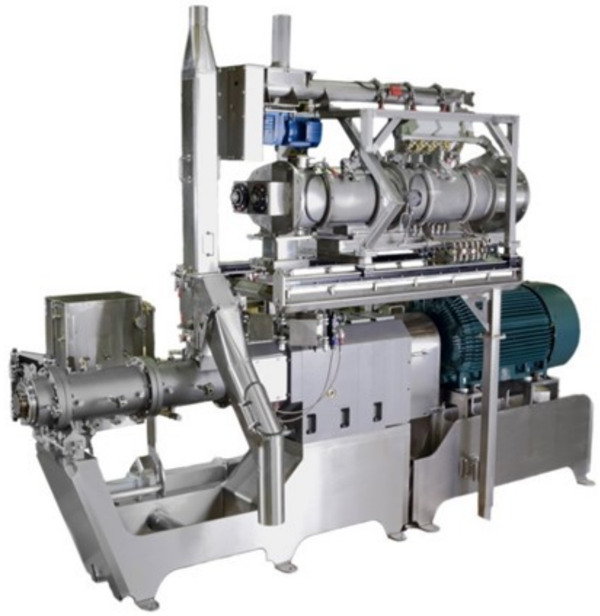


*Figure 12: **Left** - Twin screw extruder for FK - Wenger Mfg Inc. - TX85 – up to 500 kg/h FK, **Right** - a dosing system for two powder components*

Warm extrusion

In warm extrusion, hot water (~90°C) is added to the flour and micronutrient premix in an excess of up to 33% and mixed until the ingredients are homogeneously distributed (10 minute maximum) to simulate pre-cooking inside the preconditioner. After mixing, dough temperatures reach 60-62°C; however, rice starch gelatinization temperature occurs between 65 and 78°C [31]. This is resolved by a sharp rise in temperature as the dough is transferred towards the die plate, due to shear input (Figure 13 [32]).

The temperature at the die plate must remain below the temperature at which FKs begin to expand (< 100°C) to allow gelatinization but prevent puffing. The installation of a thermocouple in front of the die allows product temperature to be measured, and action to be taken if necessary. Cooling or venting mechanisms in the last section of the extruder are highly recommended to prevent dough temperatures reaching 100°C.

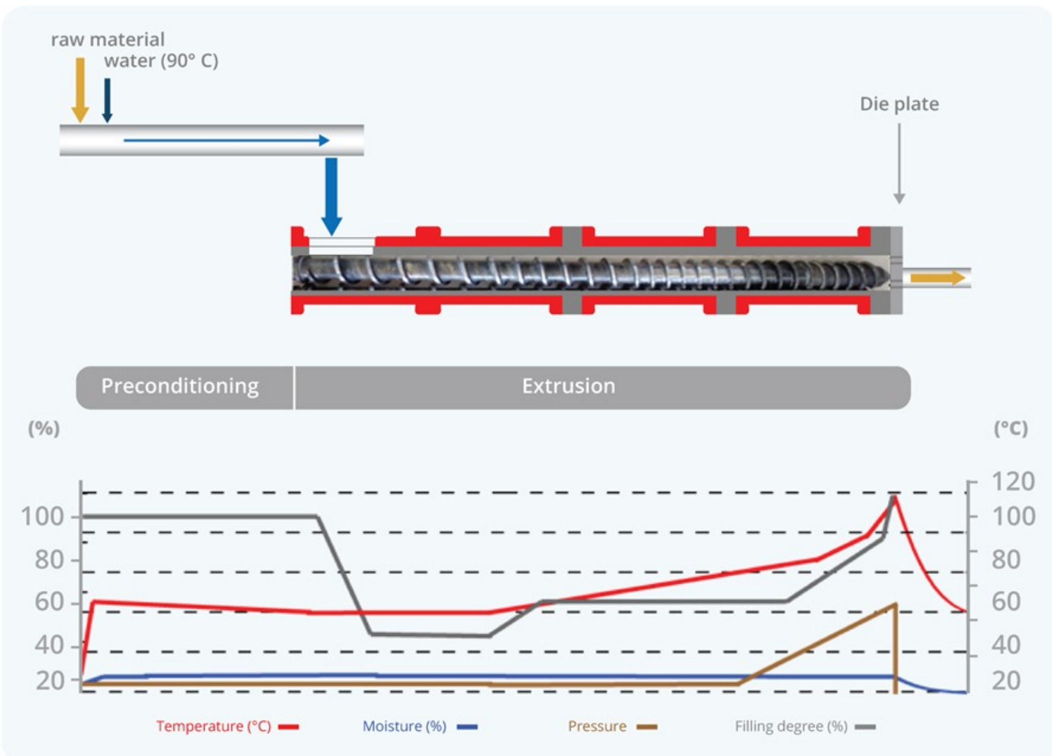


*Figure 13: **Schematic description of the FK warm extrusion process***

31 'Stärke und Stärkederivate' G. Tegge, Behr´s Verlag, 3. Auflage 2004
32 Adapted from Dr. T. Brümmer: unpublished material

UNIT OPERATION PARAMETERS

Extrusion is a complex operation. Changes in one process parameter, such as the screw speed, affect multiple product properties and other parameters. It is very important for the operator of an extrusion line to understand the correlations between changes in process parameters and their effects on product properties. These correlations and impacts are discussed below. It is recommended that specific changes in the process parameters are discussed with the equipment manufacturers during validation of the line upon installation.

Figure 14 [33] shows the single unit operations for each section in the system analytical model. In this model, product properties can be defined and changed.

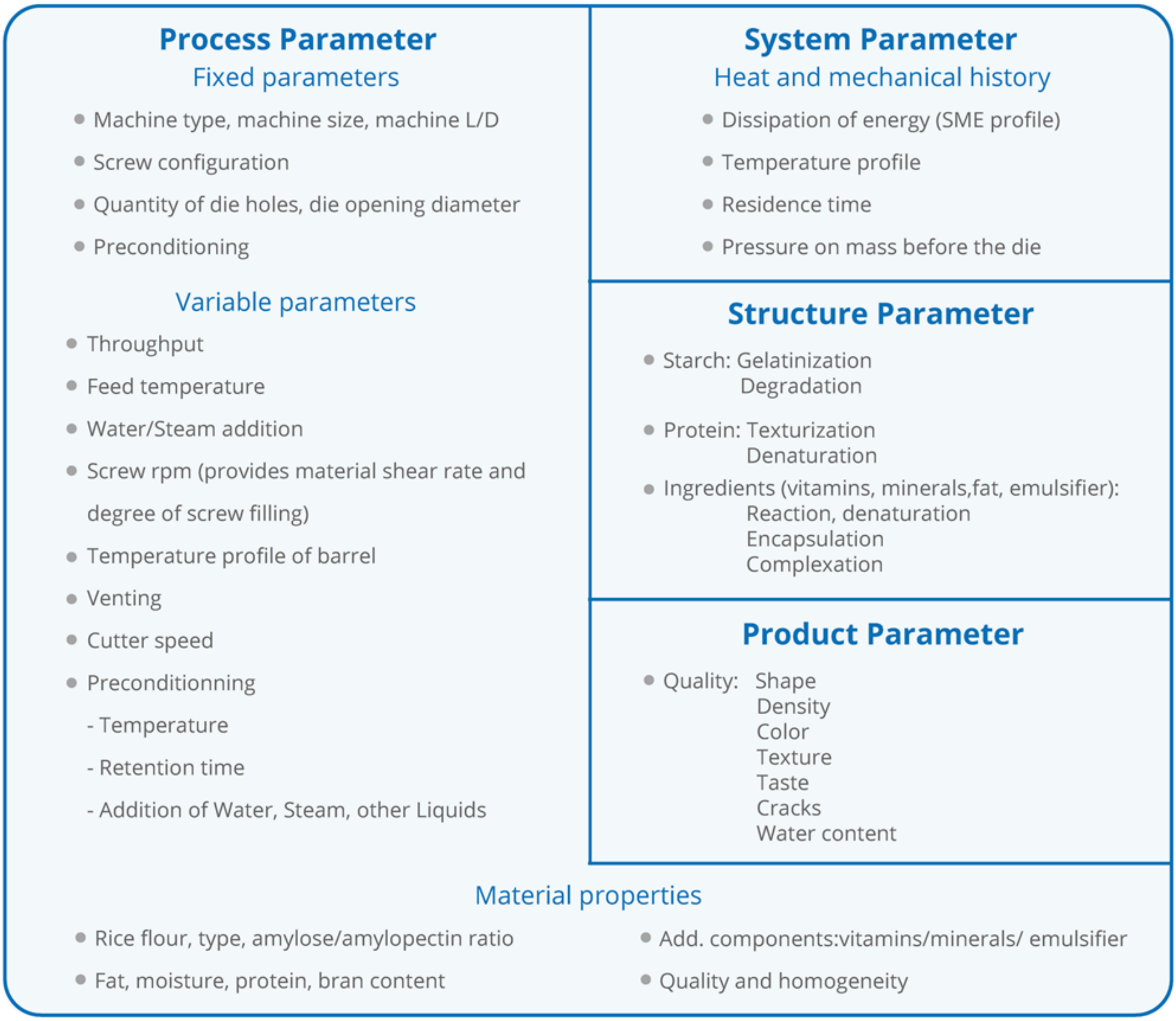


Figure 14: ***Overview in the unit operations of the sections of the model***

33 Adapted from Dr. T. Brümmer: unpublished material.

Screw Speed – dynamic response in the hot extrusion process

An increase in screw speed results in an increase in the shear energy input, represented as Specific Mechanical Energy (SME), **and the dough temperature**. This reduces the dough viscosity in the extruder. As a result, the pressure of the dough on the die plate decreases and the resulting torque of the screw also decreases. Thus, increased screw speed could be used to increase the degree of starch gelatinization, which will affect final product appearance by making the grain more crystalline. This could influence cooking properties and prevent disintegration of the cooked FK.

Throughput can also be increased if the energy input is sufficiently high before the increase in screw speed. However, the increased energy input due to the higher screw speed can also lead to high temperatures (above 100°C), which can then cause FK to expand (see Figure 15 [34]). Hence, a thermometer close to the exit is needed to measure temperature and control expansion.

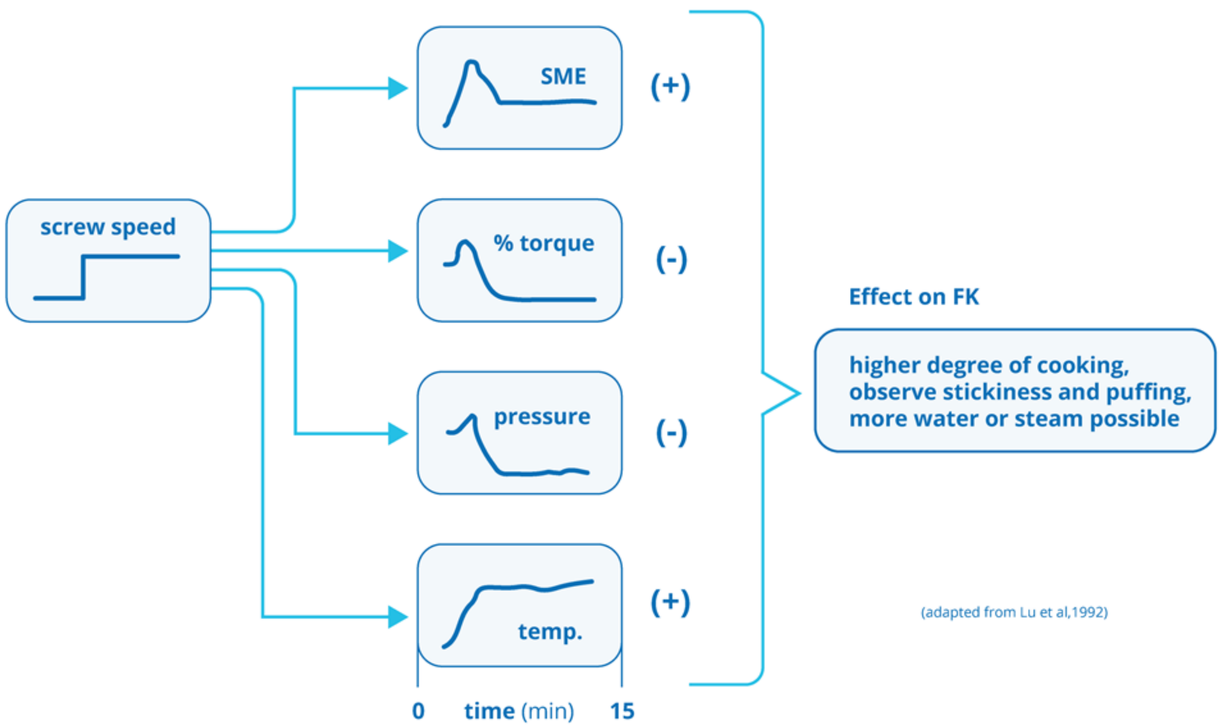


*Figure 15: **Screw Speed - dynamic response in the hot extrusion process***

Moisture Content – dynamic response in the hot extrusion process

An increase in the moisture content of the mass in the extruder reduces the input of SME and thus the input of thermal energy. This lowers the degree to which starch is cooked, as well as the product temperature of the mass. Additionally, the pressure in front of the die and the resulting torque of the screw is reduced. **This could result in a product that is less cooked**. To overcome this, the addition of water must be optimized to ensure starch gelatinization (65-78°C) and allow the backpressure of the mass inputs enough shear to cook the starch.

However, it must be kept in mind that the addition of water to the preconditioner during the hot extrusion process increases the degree of starch gelatinization. This could result in stickiness if steam is added simultaneously and block the preconditioner (see Figure 16).

34 Adapted from Dr. T. Brümmer: unpublished material.

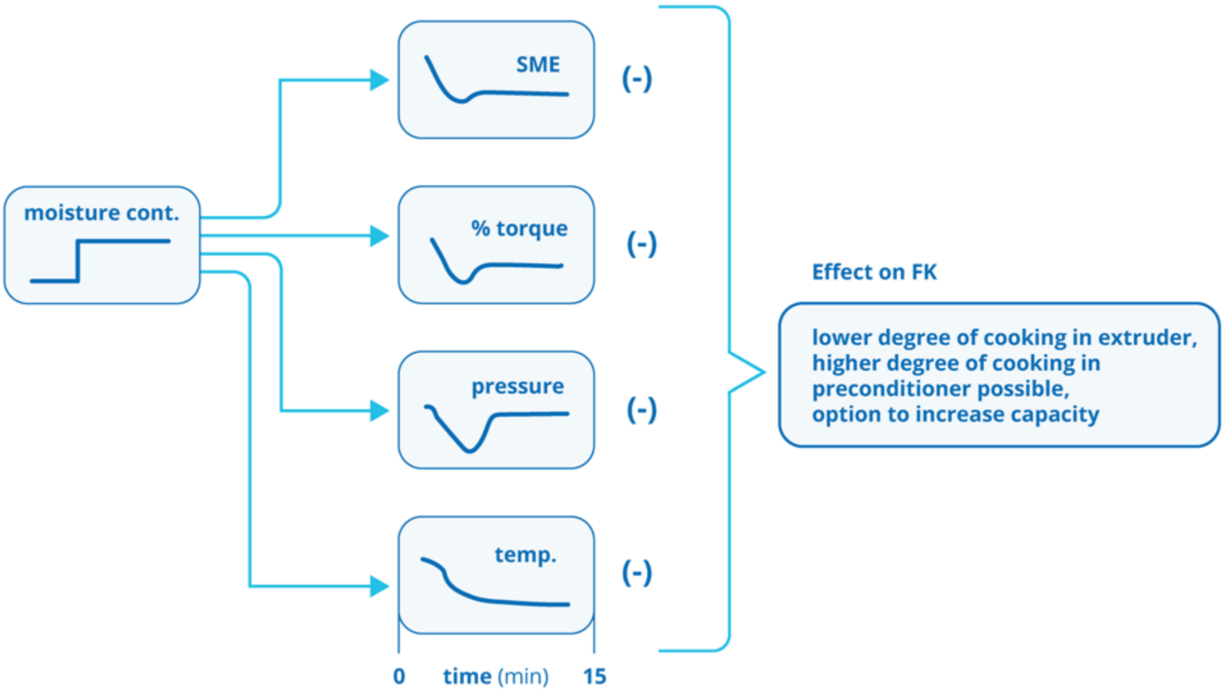


Figure 16: ***Moisture content – dynamic response in the hot extrusion process***

Feed rate – dynamic response in the hot extrusion process

Each production process should aim to run at the highest possible feed rate. However, an increased flow of flour or throughput, reduces the input of SME. This means the dough will be less processed, and the starch less cooked, triggering a higher pressure of the dough against the die plate. This increase in pressure also increases product temperature, which forces the motor to use more energy to push the dough through the die. This results in a dough with a lower energy intake and less gelatinized starch (see Figure 17 [36]).

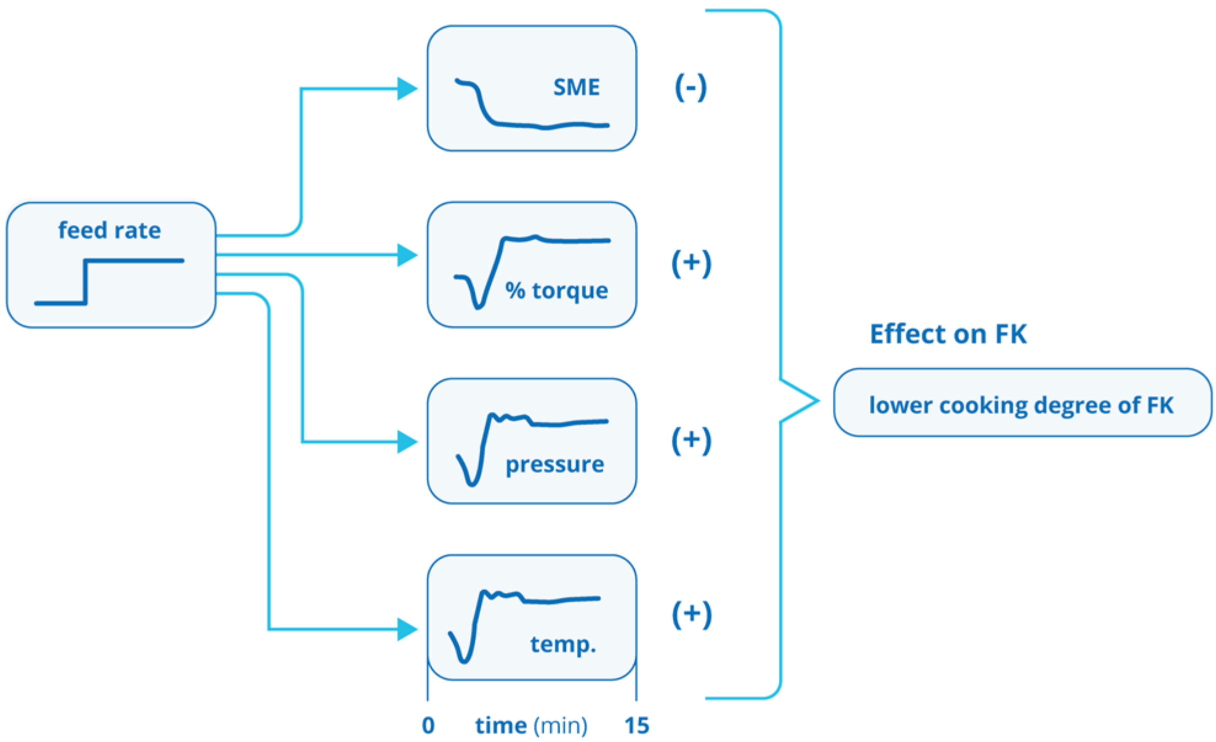


Figure 17: ***Feed rate - dynamic response in the hot extrusion process***

36 Adapted from Dr. T. Brümmer: unpublished material.

Steam addition – dynamic response in the hot extrusion process

The amount of steam added should be such that the dough in the preconditioner reaches a temperature of 90°C or more. Increasing the flow of steam to the preconditioner increases the degree of starch gelatinization. This reduces the entry of SME in the extruder because the mass gives less resistance. Consequently, the product temperature, the pressure of the mass at the die plate and the resulting torque of the screw are also reduced. The addition of steam is dependent upon the functional capacity of the flour to absorb the additional moisture from the steam and by the structural properties of the preconditioner. Excessive steam could block the preconditioner.

In warm extrusion systems, steam addition results in FK with variable degrees of cooking. Therefore, steam should be considered exclusively for hot extrusion systems, where more starch gelatinization can be achieved, and a more visually appealing FK can be processed. (See Figure 18 [37]).

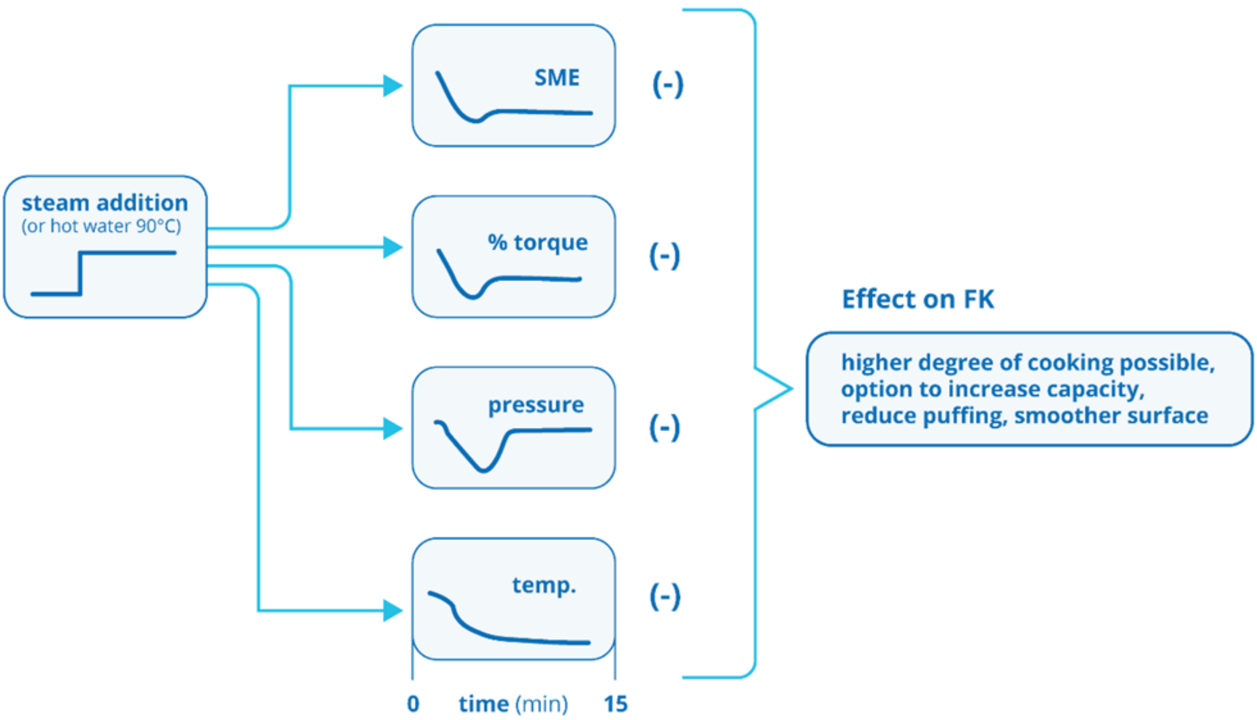


Figure 18: ***Steam addition - dynamic response in the hot extrusion process***

Emulsifier proportion– dynamic response in the hot extrusion process

Increasing the emulsifier proportion reduces the input of SME into the mass in the extruder, as the mass gives less resistance. As a result, the product temperature, the pressure of the mass on the die plate and the resulting torque of the screw are also reduced. The effect on product properties means a lower degree of starch degradation. Under process conditions where the stickiness of the product is limiting the cutting step, an increase of the emulsifier proportion may be helpful. (See Figure 19 [38]).

37 Adapted from Dr. T. Brümmer: unpublished material.
38 Adapted from Dr. T. Brümmer: unpublished material.

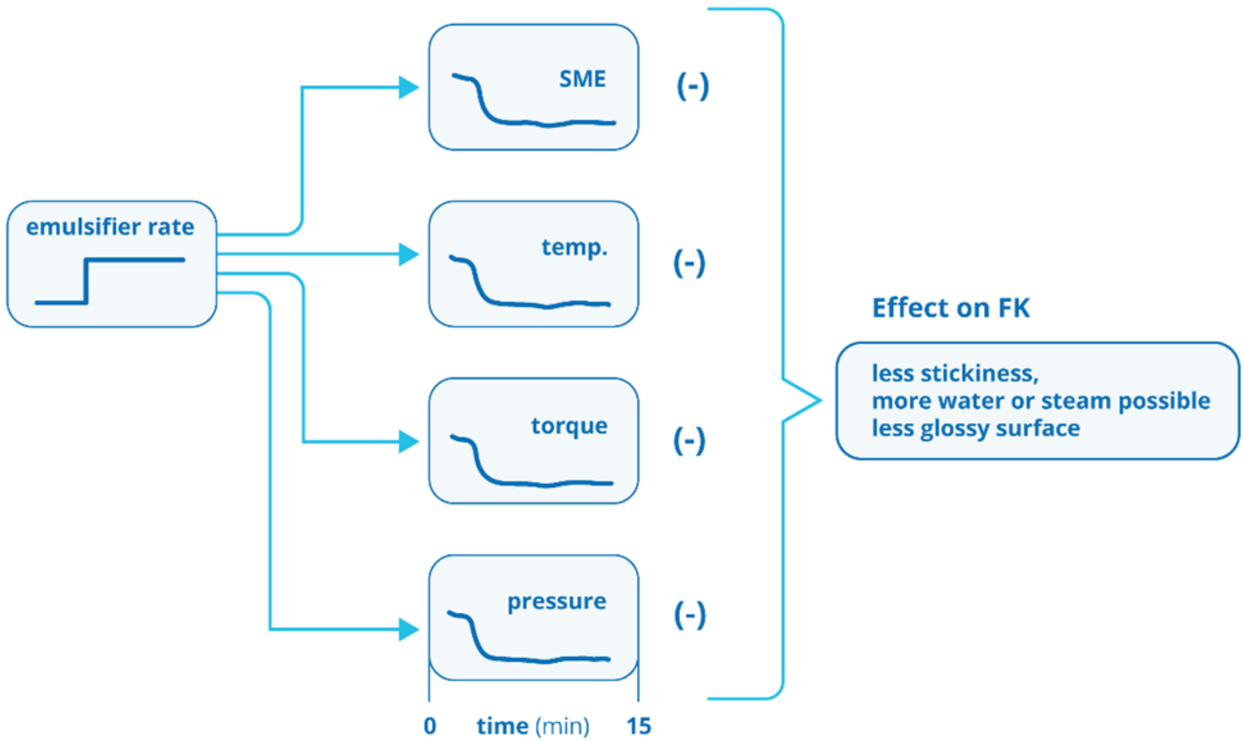


Figure 19: ***Emulsifier rate - dynamic response in the hot extrusion process***

MONITORING AND DOCUMENTING PRODUCTION FOR PROCESS CONTROL

Understanding the process model of FK extrusion is the basis for good process control and standardized production, since this is the only way to determine critical parameters and thus be able to monitor them. Accurate process control and documentation is only possible if the crucial parameters can be measured and recorded. Process data recording is an integral part of traceability of products and their manufacturing conditions.

In modern extrusion plants with a high degree of automation, all relevant parameters are detected and recorded. These include drying temperatures, belt speed, air volumes, engine power, amount of air, and the temperature in the mill. These records are especially important on the extruder. Depending on the degree of automation, all variable process parameters can be set and changed. Figure 20 [39] shows that from the central command stand, or Plant Programmable Logic Controller (PLC), the entire extrusion line can be monitored and controlled.

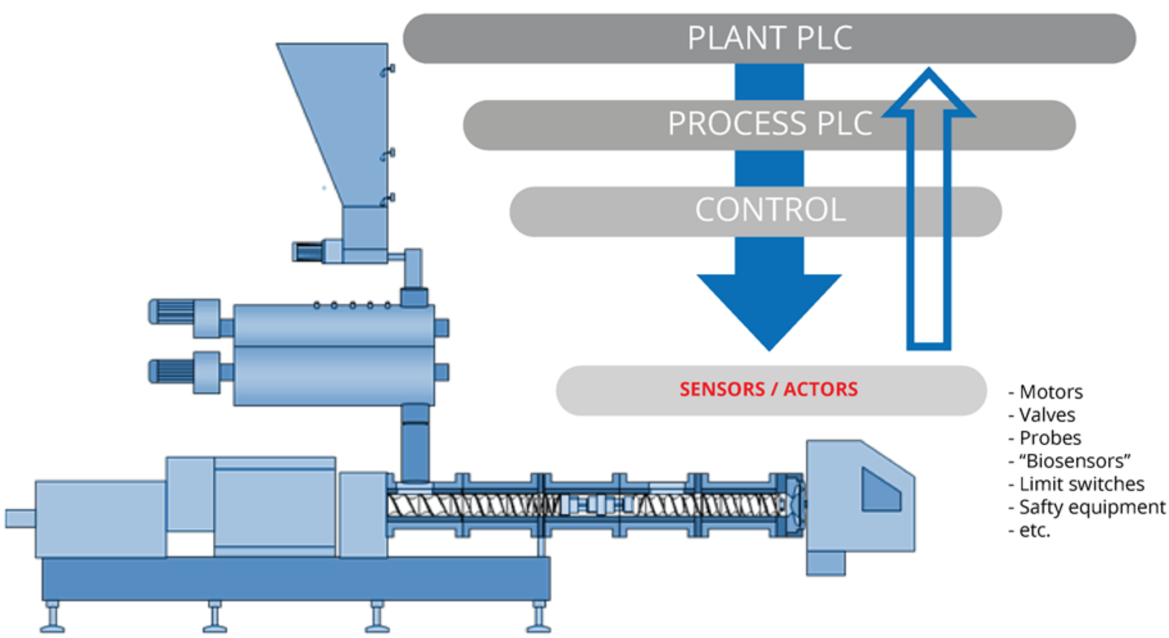


Figure 20: ***Schematic description of a process control***

39 Adapted from Dr. T. Brümmer: unpublished material.

A Plant PLC facilitates compliance with a well-defined standard operation procedure (SOP). With a high degree of automation, the parts of the plant which must be started, and the parameters needed to carry out the desired FK production, can be precisely specified. If an important production parameter (e.g. steam addition rate) is outside defined safety ranges, this is then immediately signalled and recorded. A light or sound associated with the parameter notifies the need to check and correct production. This allows the operator to react immediately and decide whether the products can be used, or the production must be stopped.

With a low degree of automation, or in the case of manual operation, the SOP can only be based on parameters that can be monitored. Therefore, the stability and reproducibility of the process is entirely dependent on the accuracy of the adjustable parameters. Compliance with the SOP is only possible if the parameters relevant to product quality are known and can be measured, changed and documented. Moreover, these parameters must be resolved as much as possible during the commissioning phase with the supplier. For example, the SOP should reflect when the extruder should be started and when the process conditions are adequate for a product that meets the parameter required (compare with Annex 1). Figure 21 [40] shows the control panels of a warm extrusion line. These panels can only measure a few parameters and there is no evidence of automated recording. This means that the stability of the process is not automatically documented. Since the defined work steps must be carried manually, this procedure is more variable and could lead to non-conformities in product or unacceptable fortified kernels.

Figure 21: ***Control panels from a warm extrusion process installation***

Automated extrusion lines have control panels close to the main components of the line, such as the extruder, and have control panels in a central plant control room (see Figure 22 [41,42]).

Figure 22: ***Extruder control units close to the extruder and as well in the control stand***

40 Dr. T. Brümmer: unpublished material

41 Bühler A.G., published and unpublished material.

42 Wenger Inc., published and unpublished material.

EQUIPMENT

Extrusion System

The heart of the FK production plant is the extrusion system. This is made up of different components, containing add-ons specific to each particular process. The extruder itself is also assembled per specific requirements in terms of throughput and conditions of the current application, namely FK.
Figure 23[43] shows a schematic extrusion system which can be used for the FK process. This system consists of the following components: dosifier/feeder, preconditioner, water and steam addition devices, extruder, heating/cooling for extruder barrels, control cabinet, and an optional degassing device. Each component is selected according to the desired throughput, the process, final desired attributes, and budget. They are then activated and adjusted by the extruder control during production.

There are different options on the market for all these components. Therefore, the layout of the extrusion system should be carried in close cooperation with the supplier.

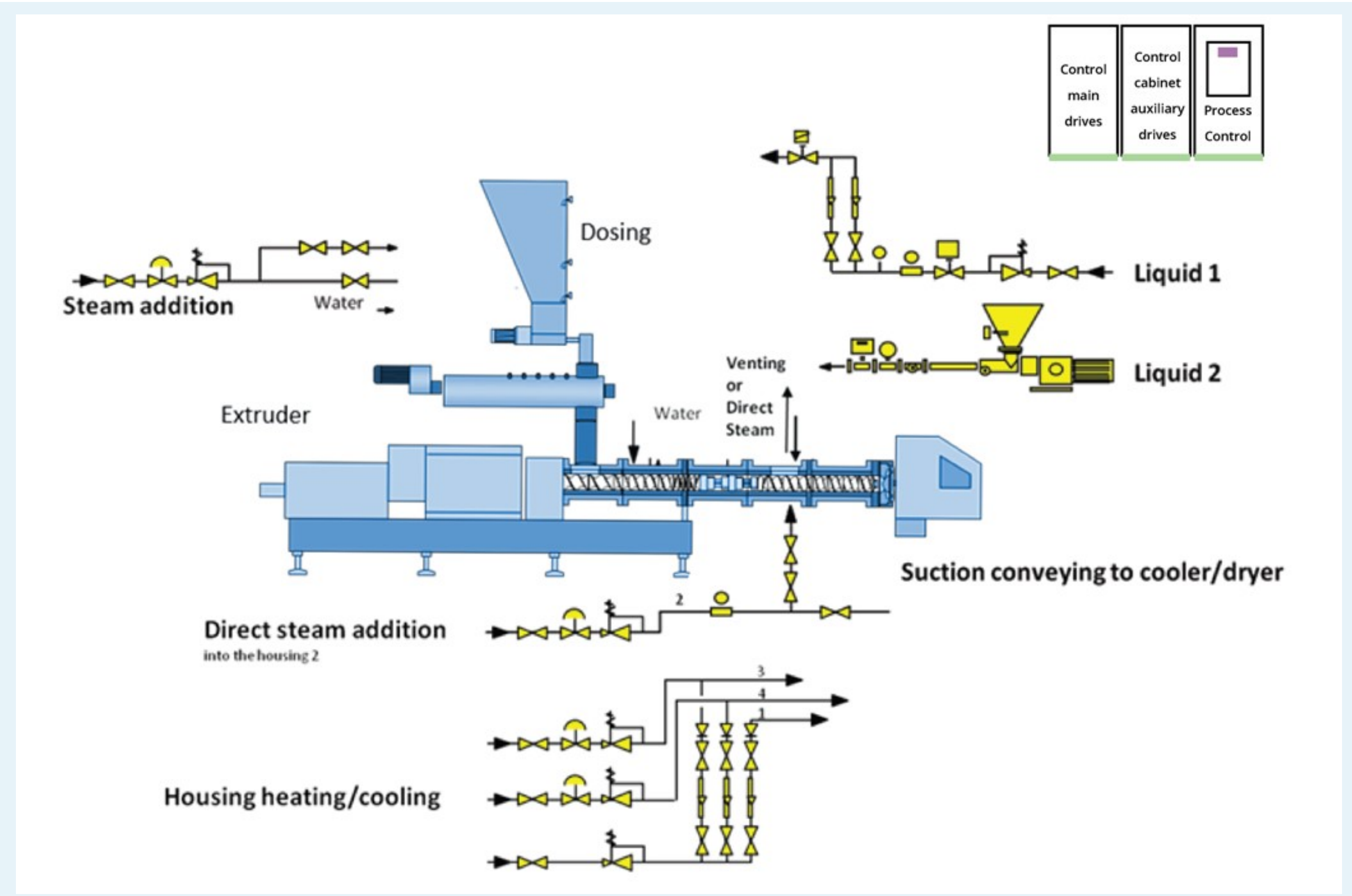


Figure 23: Schematic overview of an extruder with different surrounding components

Dosing

The two ways to feed the flour blend into the extrusion process - volumetric and gravimetric - both consist of a premix hopper and a dosing screw. The screw continuously feeds the flour from the hopper into the extruder. Since these two systems function very differently and require very different investment, it is important to describe them in detail.

43 Adapted from Bühler A.G., published and unpublished material.

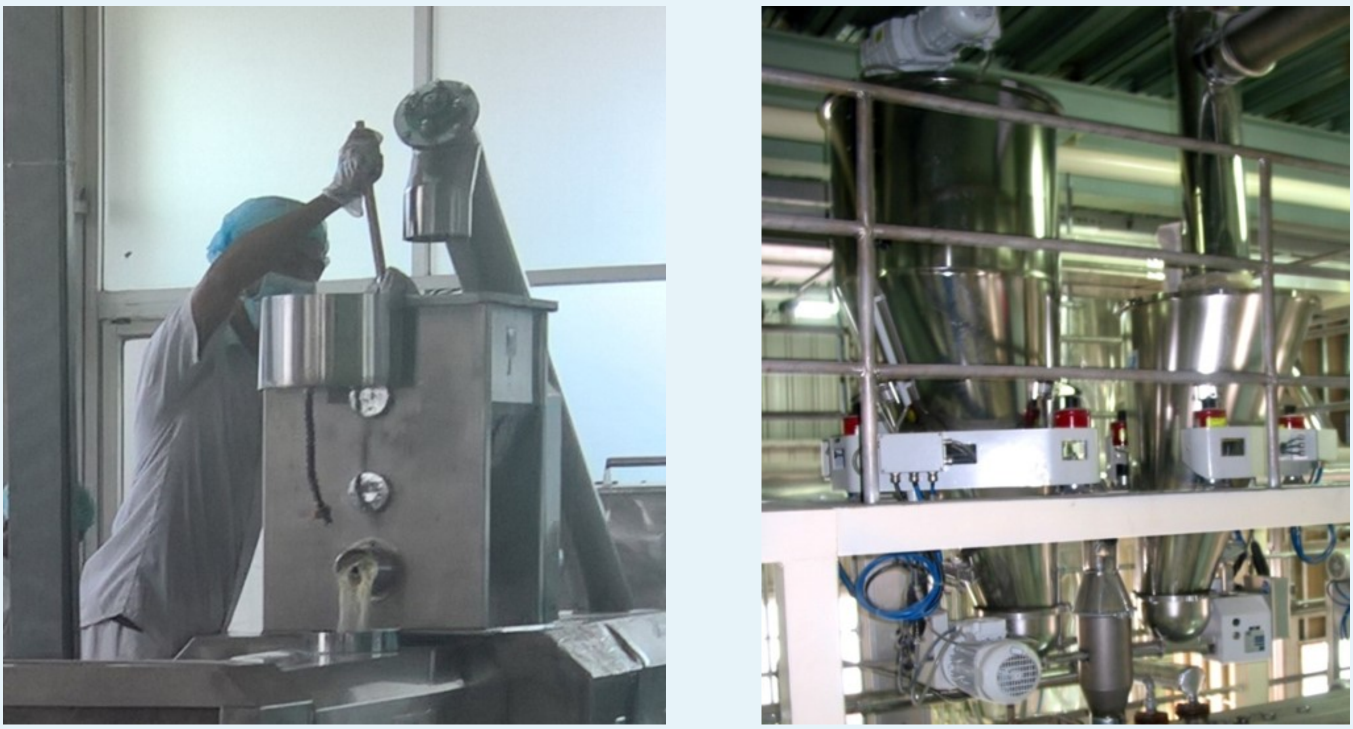
Volumetric dosing

This system works by changing the speed of the dosing screw. It does not consider the density of the material, or the degree to which the hopper is filled. It simply promotes a filling of the screw chambers per revolution forward. The mass throughput of the dosing screw differs with different bulk densities of the material and the bulk weight of the material in the hopper. Furthermore, the fill level in the hopper affects flow rate due to the pressure exerted by gravity. This effect can be reduced with a large container and a high frequency of refilling. With a volumetric dosing system, the actual throughput for the respective premix must be determined manually in advance. For this purpose, the mass flow at different speeds must be collected and weighed for a certain time. Based on these measurements, a metering curve can then be calculated to determine the mass flow of the premix for each screw speed, which is specified by the control unit. However, this is only an indicator of throughput and the actual level depends on the accuracy of the control. Often, the speed of the dosing screw cannot be specified precisely because these are mostly controlled by potentiometers, which show only a rough percentage scale. Volumetric dosing is therefore very difficult to integrate into any kind of process automation and thus is usually used in semi-manual and manual lines.

Gravimetric dosing

This system is much more complex but also much more accurate. Here, the hopper is on load cells that continuously measure the weight of the material in the hopper. This allows the system to accurately calculate the output of the feeder at any time. Thus, the system constantly changes the speed of the metering screw to the desired rate. In addition to the very accurate continuous feeding rate, the system generates data that may be retained as a record of the production process. For a reproducible process, it is necessary to obtain and document these throughput data, otherwise there is no real control over key factors affecting product quality.

Figure 24[44] shows volumetric and a gravimetric dosing equipment, highlighting the different complexities in the two systems.



A **B**

*Figure 24: **A)** Volumetric dosing with a single feeding screw; **B)** Gravimetric dosing units, one for rice flour and the smaller one for the vitamin, mineral and emulsifier premix*

44 Pictures by Dr. T. Brümmer

Preconditioner

A preconditioner homogeneously mixes the blended rice flour and fortificant mix with steam and water. The aim is to obtain moistened rice flour particles and to gelatinize the rice starch within these flour particles. Maximum amounts of both water and steam should be added to the preconditioner, and the ingredients must stay in the conditioner for as long as possible at the highest possible temperature. Settings for water and steam addition rate as well as throughput depend on the design properties of the preconditioner, the rice type and the recipe. During start-up of the extrusion line, these parameters are usually set with the equipment manufacturer during validation of the product. In general, preconditioning time should allow water content between 30 and 35% including the steam. Additionally, the proportion of steam in the moisten flour (about 8-10% of the flour) should allow the mixture in the preconditioner to reach a temperature of about 90 to 95°C. A suitable residence time for the FK process in the preconditioner is about 3 minutes. In Figure 25 [45] the most common preconditioners are shown.

*Figure 25: Two of the most common preconditioners used for extrusion, **A)** Bühler preconditioner - BCTC; **B)** Wenger preconditioner - HIP*

Extruder

Figure 26[46] shows an overview of the typical components in a standard extruder. In general, an extruder consists of the following components: motor, gearbox, barrels, screw, die plate and cutter. These components are further described below.

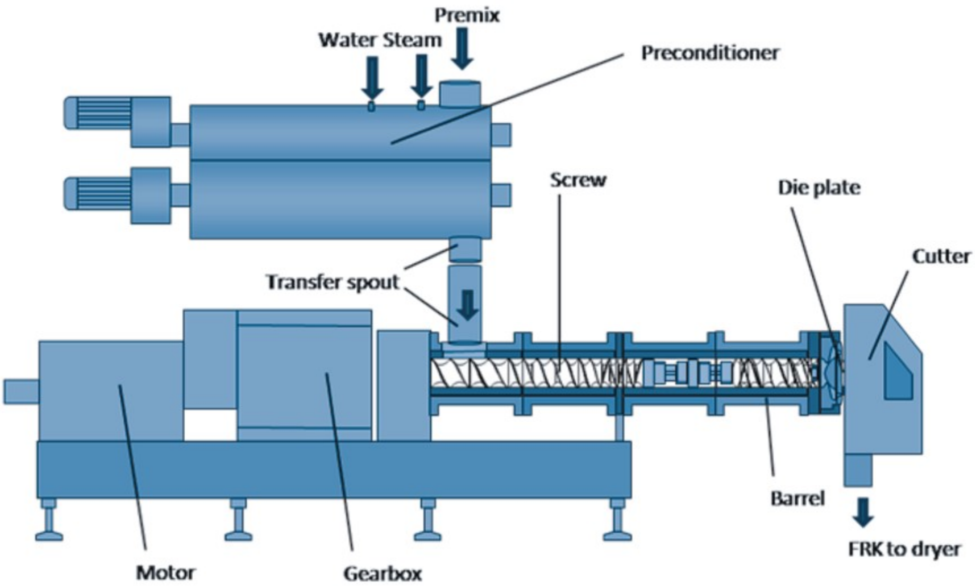


Figure 26: Schematic overview about an extruder with its typical components

45 Picture left by Bühler A.G.; picture right by Wenger Inc.
46 Adapted from Dr. T. Brümmer: unpublished material.

Screw

The most important component of the hot extrusion process is the configuration of the screw and the arrangement of the individual screw elements. Rice flour that has been gelatinized in the preconditioner will still have a granular floury texture upon entry to the extruder. This powdery state must be converted in the extruder into a homogeneous dough without any granular appearance through shear. This shear energy is transferred according to the configuration of the screw elements. In the case of hot extrusion, screws consist of a screw shaft and of individual elements, as shown in Figure 27[47]. These elements have distinctly different properties that can be grouped into three types: elements with mainly conveying properties, mixing properties and shear properties (for more detailed information about different screw elements and their functionalities please contact the authors or the specific supplier). These different elements can be configured so that the dough is subjected to sufficient shear force; and the particles in the dough are dissolved and no longer visible in the final product (see also Figure 4 on page 15).

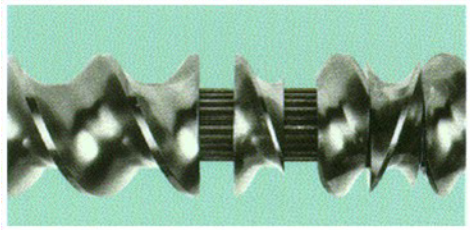


Figure 27: Screw elements during assembly on the screw shaft

Screws used in the warm extrusion process (see Figure 28[48] below) are a single unit and not comprised of individual elements. Thus, they cannot be configured to optimize the shear force. These screws have a purely conveying property. The only additional feature of the screw is to increase the fill level by increasing the integrated pitch towards the end. In such a screw configuration, the material is conveyed through the extruder barrel only for a certain time, which is set or changed only by the screw speed. During this time, the material has some contact with the heated cylinders of the extruder, and limited heat transfer occurs. However, this depends on the ratio of the inner surface of the extruder to its inner volume. This means that the larger the extruder diameter and higher throughput, the lower the heat transfer will be. This is because dough is only being conveyed, the shear force cannot be optimized further, and only a very limited heat transfer from the housing is possible. For this reason, investment in flexible screw design with different elements is of utmost importance. In warm extrusion, the energy input that produces the characteristic FK is generated due to the backflow of the dough against the die plate. The backflow of the mass and the internal friction caused by the forward pressed dough increases the temperature and results in the shaping of the FK. Due to limited options to adjust the process, it is quite possible to exceed the product temperature needed and cause the FK to expand. An expanded product means a significant loss of quality.

Figure 28: Screw for the warm extrusion process, single piece design without options for changes

A flexible screw configuration is always preferable because the flexible screw elements can be used to create internal shear. Thus, the introduction of mechanical energy can be forced at different points other than the die plate. This enables the dough in the extruder to be cooked independently of the limited temperature transfer of the housing elements. Figure 9 (page 23) shows the process length of the extruder can also be used to cool the mass after leaving the cooking zone, thereby preventing expansion upon exiting the die plate.

As discussed in hot extrusion on page 31, degassing, against the environment or even under vacuum, significantly increases the flexibility of the process (see Figure 2) and can be used in warm and hot extrusion. By degassing, a significant amount of water can be removed from the process as steam. As a result, the mass in the extruder is cooled significantly. This decreases the dough temperature at the die plate, and thus the tendency to expand. Furthermore, degassing can cause the process to increase water addition rate and increase throughput.

47 Picture by Bühler AG
48 Picture by Dr. T. Brümmer

Die plate

The dimensions and arrangement of the holes in the plate and the head space between screw and die plate determine the FK shape and uniformity (see Figure 29). The width, length and depth of the holes in the die plate are the major factor affecting FK final shape. The length and width of the kernels can be adjusted by the extrusion parameters only to a small extent. The dough in the extruder must be homogeneously distributed over the entire die plate to force the same amount of material through each die hole. Only a good knowledge of the behaviour of the dough in the extruder and the die area, and the design of these components, can achieve homogeneous end-product shape and size.

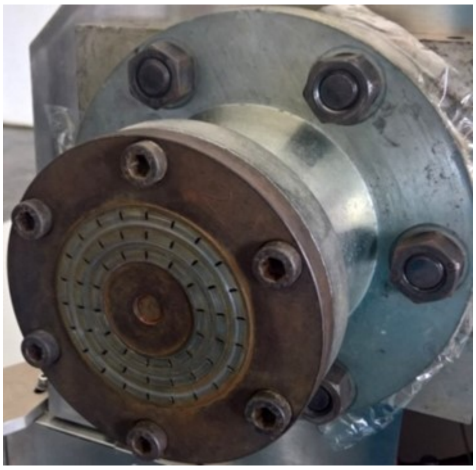


Figure 29: Example of a die plate from a warm extrusion process (300-400kg/h)

Cutter

The dough exits the extruder through the die holes as a continuous strand. This strand must be cut with rotating knives to obtain the characteristic rice-like kernels (Figure 30 [50]). The number of knife blades and the speed of the knife shaft determine how often the strand is cut off. This it is what gives the third dimension, or height, to the kernel.

It is necessary to specify and vary the speed of the blade shaft. Furthermore, if the distance from the knife blades to the die plate can be adjusted during the process, it is possible to optimize the cut. This can minimize rough edges, cut corners, smears and stickiness to the knife blades. For example, an increased emulsifier addition, higher knife speed and fewer knife blades optimally adjusted to the die plate usually help minimize sticky kernels. A controlled cutting process will give the best FK.

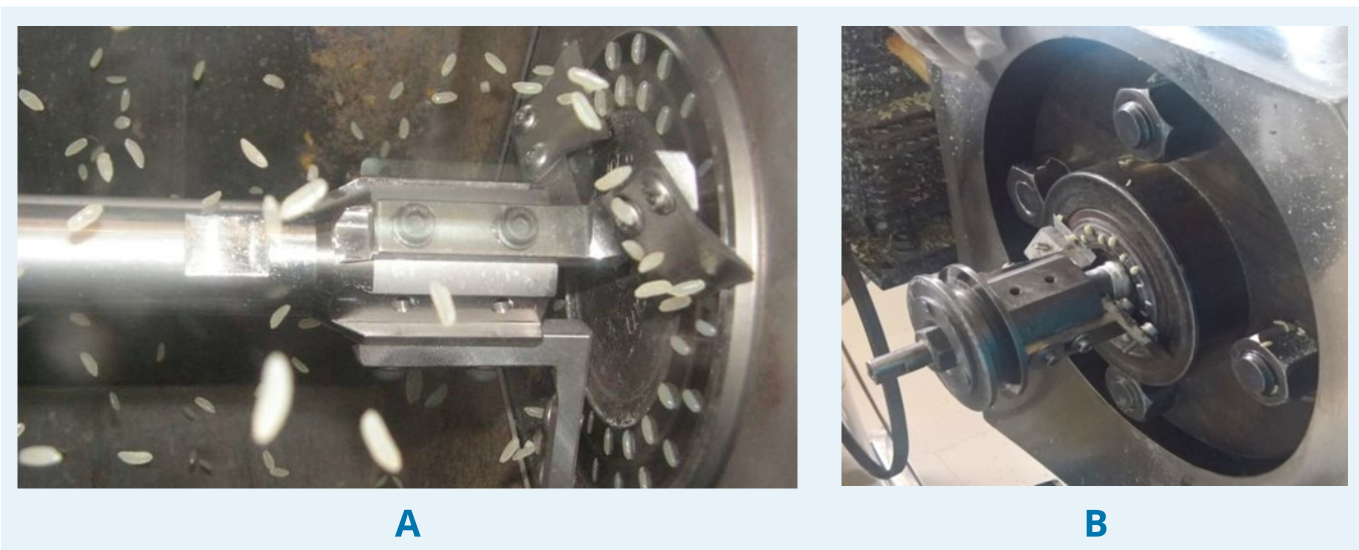


*Figure 30: Different die options from various suppliers; **A)** Cutting Head with adjustable distance of the blades to the plate in a hot extruder; **B)** Warm extruder, with fixed installed blades.*

50 A: Picture from Bühler A.G., Aug 2018: Bühler Solution of Rice Fortification; B: picture by Dr. T. Brümmer

Heating /cooling options in the extrusion process

Temperature is a key parameter for FK process, capacity and quality. It is helpful to be able to measure the product temperature in the process, and important to be able to change the product temperature within the zones of the extruder. Measuring the temperature of the housing gives no reliable indication of the actual product temperature due to the limited heat transfer from the housing, even if the housing elements are actively heated or cooled. Therefore, to measure product temperature, a sensor must extend into the actual product inside the housing.

Cylinder temperature is an important control mechanism in the FK process. Even if the heat transfer from the heated or cooled cylinders is rather limited due to the surface volume ratio, active heating or cooling of the cylinders helps stabilize the process conditions. In the case of warm extrusion, extruders are usually equipped with electric heating shells, which heat the barrels to a set point (see Figure 31[51]). Since the housing units cannot be cooled, overheating can occur – especially in front of the die plate, where heat is generated by the backpressure against it. In warm extrusion systems, the backup at the die plate is the only way to cook the flour premix into an amorphous dough. To support this, the barrel temperatures of the first sections should be set as high as possible, to transfer as much thermal energy into the dough as early as possible. The goal is to achieve starch gelatinization in the conveying section, so the temperature increase can be limited at the die plate. However, the best option would be to cool the last section of the extruder to better control the process and to further increase the end-product capacity.

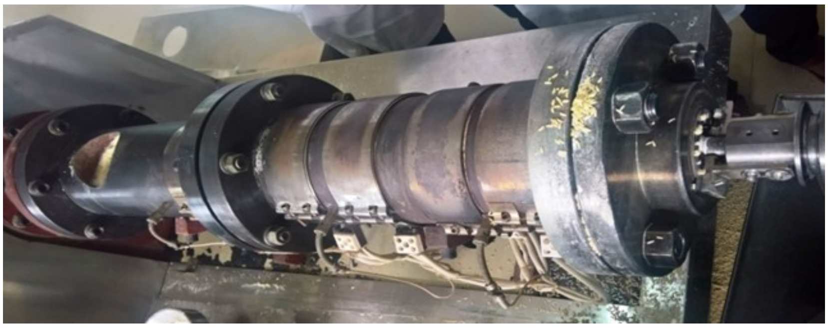


Figure 31: Extruder barrels with external heating shells

In general, the goal is to generate the required energy for an extrusion process from the screw configuration and the speed of the screws. This process is referred to as the transfer of motor power to mechanical energy. This energy is what affects the dough in the extruder and it is expressed as SME in watts hour/kg (Wh/kg). In hot extrusion, however, this is only partially the goal. Here, the SME input is only required to dissolve the precooked flour particles and to transform them into a homogeneous mass, so that a good FK quality can be achieved. However, as this SME entry also causes an increase in temperature (and thus the possibility of an expanded product) the energy input due to the SME must be compensated by removing energy. Therefore, controlling the temperature of the extruder barrels is a good option to increase the efficiency of the process.

Well-designed extruder barrels offer the possibility to heat or cool the barrels. The most common option for temperature control is external heating devices which pump a tempered medium (i.e. water, oil or glycerine) through the cylinder. Thermocouples control the operation of these external devices and ensure production at set points. Alternatively, electrical jackets can be used for heating, and water (chilled or at room temperature) for cooling. Thermocouples monitor the energy output through the shells, or the opening time of the cooling water valves, to bring the extruder barrels to the temperature set point. Another possibility is the use of steam. Again, thermocouples monitor the valves to heat the extruder barrels with steam or to cool them with water.

The selection of the tempering medium defines the possible temperature range. Hence, the tempering medium should be selected according to the requirements of the process and operating cost related to electricity or steam in collaboration with the equipment manufacturer. Additionally, the precise control of the process temperature gives the best results in terms of FK quality at the highest possible capacity (kg/hr). Figure 32 shows options controlling process temperature.[52]

51 Picture by Dr. T. Brümmer
52 Adapted from Picture of Bühler machinery, photographed by Dr. T. Brümmer

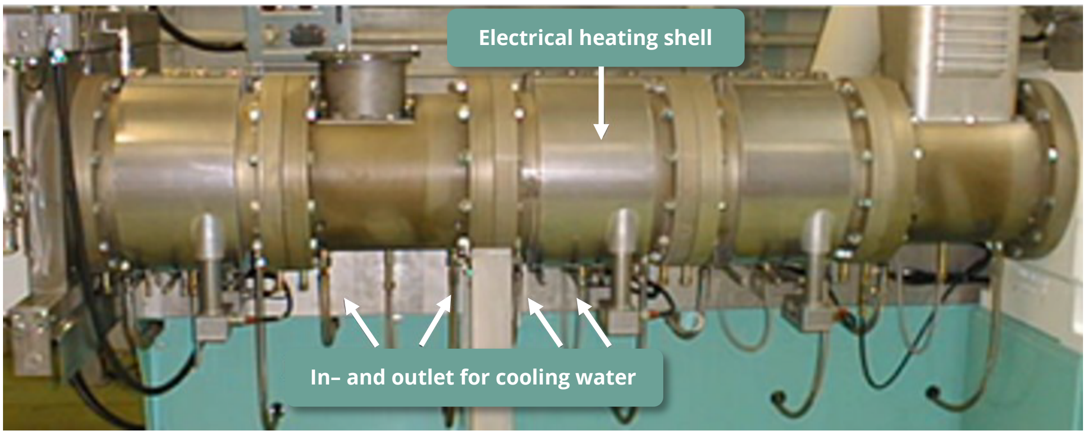


Figure 32: Options for heating and cooling a barrel with an external thermal device and heating shells

3.5. DOWNSTREAM PROCESS AND EQUIPMENT

Downstream components include equipment that enables processes after extrusion (see Figure 33[53]). The kernels formed and cut on the extrusion die plate must be dried and cooled before they can be stored or packaged. Moisture content and temperature are most important for a stable FK product.

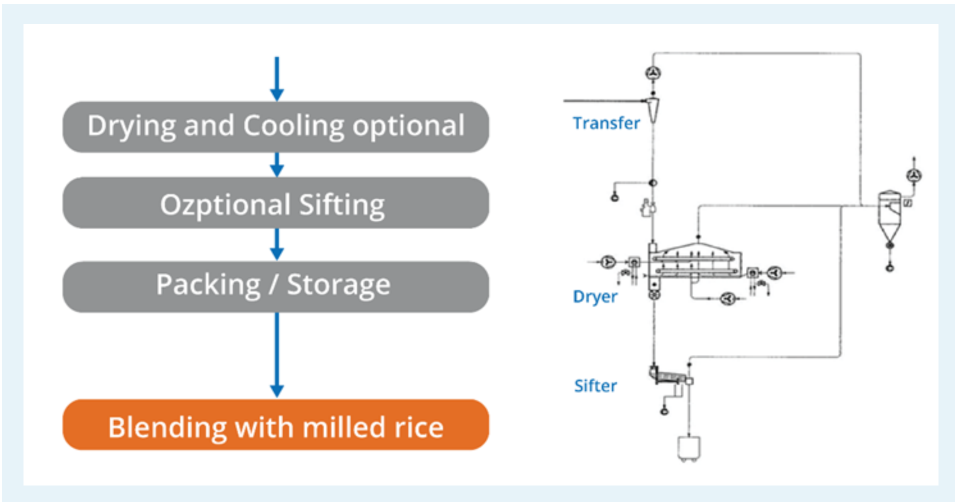


Figure 33: Schematic overview on the downstream process and its equipment

TRANSFER TO DRYER

The cut kernels from the warm extrusion process can be transported to the dryer with a non-stick conveyor belt or vibratory conveyor (see Figure 34[54]). Kernels from the hot extrusion process should be transported through a pneumatic conveyor due to their stickiness at this stage. Also, pneumatic transport is a good way to dry the surface of the hot extruded kernels, thereby reducing the formation of lumps in the subsequent dryer.

Figure 34: Vibratory conveyor

54 http://www.chinafoodmachinery.cn/index.php/Product/viewequ/id/138.html

DRYING

For warm extruded FKs, a long-term belt dryer may be the best option. This is because the kernels are normally produced with lower moisture content, and so they are less sticky at the end of the extrusion process.

For hot-extruded kernels, it is best to use a two-stage drying process. Figure 35[55] shows a typical drying curve in a hot extruded product. The rapid initial water loss (Phase 1) suggests that the FK drying process is initially determined by air exchange (quantity and temperature). This is followed by slow water loss, as the drying process is limited by the diffusion of water from inner layers of the kernel (Phase 2).

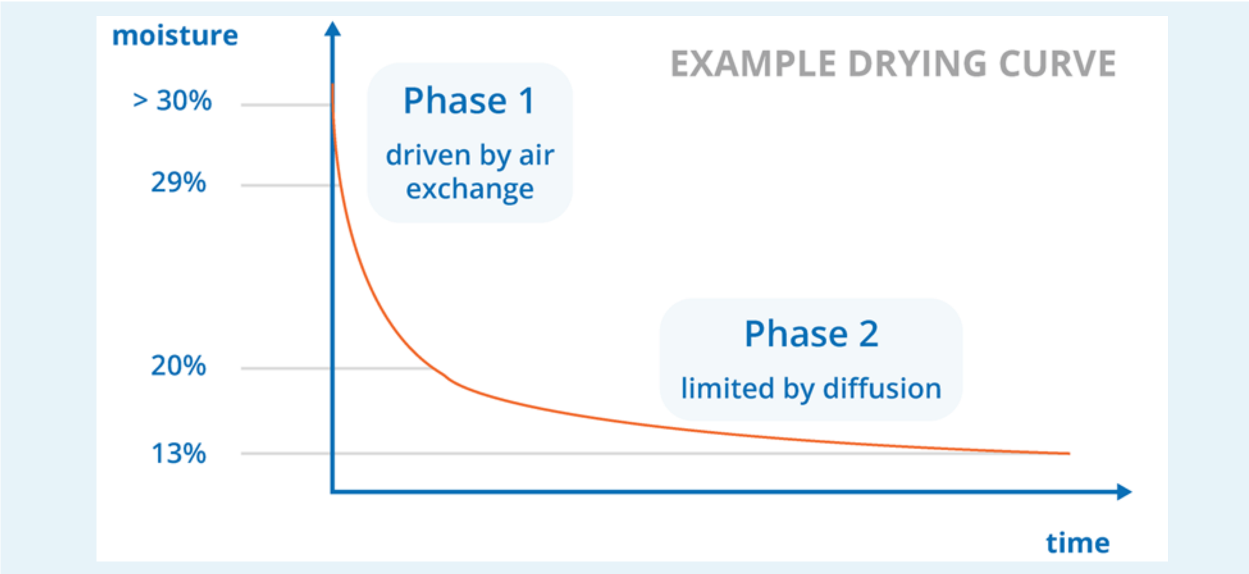


Figure 35: Schematic description of the drying curve of FK

It is preferable to divide the drying process into two machines: one with a high air throughput, like a fluid bed dryer, and a second one with a long residence time, such as a belt dryer (see Figure 36). In Phase 1, a fluid bed dryer is recommended as it actively moves the kernels through the air stream, preventing sticking. Due to the high airflow, a large amount of water can be removed in a very short time. A long-term belt dryer can complete the drying at moderate temperatures (Phase 2). This should be carried out at as moderate as possible temperatures to prevent excessive drying of the outer layers, which will result in cracks. These cracks can lead to the breakage of the kernels during handling, which is a significant quality loss.

*Figure 36: **A)** Fluid bed dryer "OTW", Bühler AG; **B)** Belt dryer/cooler "Airflow", Wenger Inc.*

55 Adapted from Bühler A.G.

After drying, it is very important that FKs are cooled to near ambient temperature so that condensation does not occur during packaging. Condensation can lead to moulding during storage. Also, unevenly or overly dried kernels crack, which leads to breakage and lower acceptability.

In terms of plant economics, it is important to choose the best option for generating the energy needed for drying. This energy can come from electricity, gas or steam, and requisite components must be included in the calculation of economic efficiency. It may also be possible to use residual heat from other processes.

Recently, a three-stage drying was described by Bühler[56] as the optimal drying process for hot extruded kernels. It was reported that after a short time in a fluidized bed dryer (10 minutes at 65°C) and a short cooling phase (3 minutes at 40°C), FKs had dried to an average water content of 15%. To compensate for the moisture gradient within the kernels, which are drier in the outer layers, an isolated belt conveyor with an approximate residence time of 60 minutes was used to equilibrate the moisture content without any further input of thermal energy. The desired final moisture content was achieved in a third machine, another fluidized bed dryer. It was described that air at 60°C with residence time of 8 minutes drying and 3 minutes cooling was needed to dry FKs from 15% to about 12.5% and to cool the FKs to room temperature. These final conditions (moisture and temperature) are ideal for optimum storage.[57]

INFLUENCE OF DRYING CONDITIONS ON FK

Drying has a significant influence on the appearance of FK.[58] Figure 37[59] shows FKs that were extruded using the same extruder; but dried at an ambient temperature of ~25°C for more than 40 hours (A) or in a fluidized bed dryer at 90 °C for two hours with strong air movement (B). The latter presents a blunt surface and significant shrinkage, which highlights that drying as gently as possible is advised.

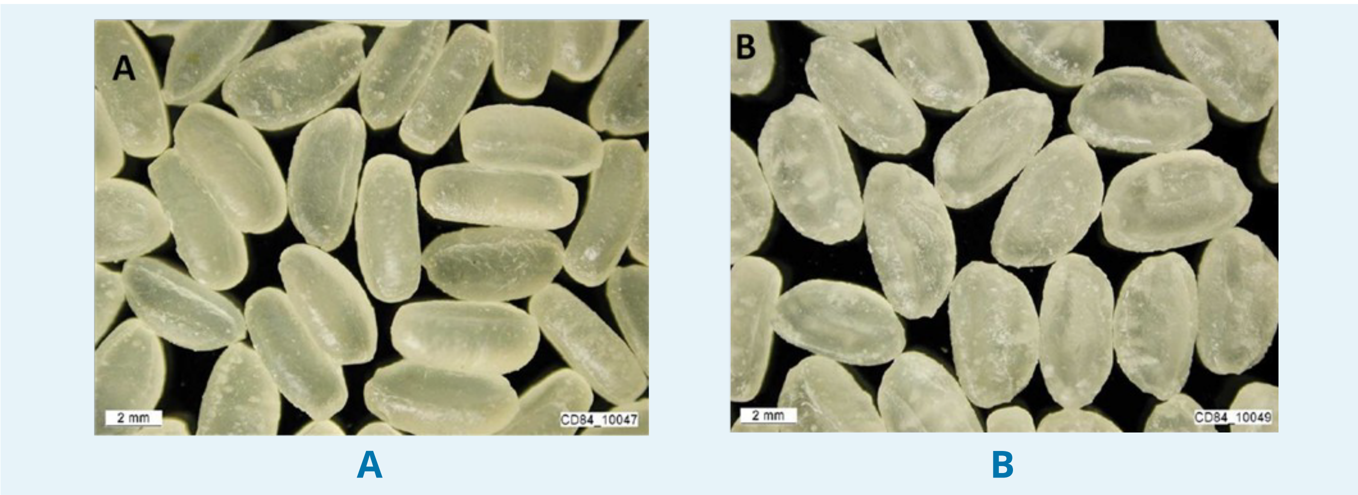


*Figure 37: **A)** FK dried at ambient temperature (~25°C) for >40h; **B)** FK dried in a fluidized bed dryer at 90°C for ~2h*

STORAGE, PACKAGING

While the final moisture content of the kernels is the most important factor for FK shelf life and its micronutrient content, it is equally important that FKs are stored and packaged under the best possible conditions, namely at room temperature (approximately 23°C), away from direct sunlight and in a well-ventilated area.

It is recommended that storage time in tanks is minimized, and that FKs are packed in 5 - 25 kg bags as soon as possible. The best storage conditions for bagged FK can be created by excluding oxygen, moisture and direct light exposure. Therefore, packaging specifications should be very clear about barrier properties related to moisture, oxygen, light barriers and other characteristics that must be followed by the FK producers unconditionally. This is especially critical if FKs contain micronutrients whose stability is sensitive to direct light, moisture or prolonged storage.

All information regarding packaging and storage should be discussed with the customer.

There are many packaging machines on the market, from fully automatic to manual. Choosing a system with a high capacity is recommended, so that packaging is faster than production and can be operated independently from production.

56 Bühler A.G., Aug 2018: Buhler Solution of Rice Fortification.
57 Bühler A.G., Aug 2018: Buhler Solution of Rice Fortification.
58 Bühler A.G., published and unpublished material.
59 Pictures by Dr. T. Brümmer.

3.6. WORKER SAFETY

The FK process, like all extrusion processes, works with equipment that has high-speed moving parts. Modern plants should pay attention to product quality and durability of the machine components as well as ensuring the operators' occupational health and safety (Figure 38[60]).

- All components that move at high speed, such as the screw, blender and cutter, should be equipped with safety devices so that no one can reach into these areas.
- Electrical plugs and connections should be covered to provide protection from water, and thus prevent injuries.
- Processing conditions can increase the pressure inside the extruder barrel extremely quickly. Therefore, the extruder barrels and die plates must have a guaranteed strength against pressure. Additionally, pressure during processing must be monitored so that the process can be stopped before the pressure exceeds critical limits.
- Emergency buttons that stop the entire system immediately in the event of an emergency are recommended at least at the electrical switch and control cabinet, but also at some exposed points in the system.
- Personal protective equipment for operators includes clothing; footwear; and head, ear, nose and mouth protection from processing equipment.
    - ♦ Clean and adequately fitted clothing is not only a hygienic practice, but also assures operators' safety. It must not be too loose, or it may become trapped in running equipment during handling.
    - ♦ Due to the weight and temperature of some machine parts and materials, sturdy and covered footwear, preferably with a steel toe cap, is needed.

*Figure 38: Examples for safety options, which should be integrated in a process line; **A)** Emergency Stop Button; **B)** Safety warning stickers; **C)** Electrical safety plugs*

4. Investment and cost for FK production

The capacity of the process line is one of the most important factors affecting investment. The capacity in kg/h is therefore a crucial value to compare amongst different suppliers in addition to cost, quality, degree of automation, process controls, guarantees, maintenance, technical service, etc. The authors do not make any recommendations regarding specific suppliers or their equipment.

Table 2[61] shows estimated costs for fully automated hot extrusion lines. These very general numbers can vary from final investment decisions resulting from discussions between suppliers and customers. Warm extrusion lines can vary in cost from 30,000 USD to 500,000 USD.

Table 2: Examples of investments for hot extrusion lines

Capacity (kg/h)	Extruder – size screw diameter (mm)	Budget (USD)
300-500	62 - 85	1,5 – 2,2 Million
500-1200	93 - 115	2,4 – 2,8 Million
1000-2500	125 - 144	3,0 – 3,5 Million

60 Pictures by Dr. T. Brümmer
61 Adapted from Bühler A.G., published and unpublished material, and Wenger Inc., published and unpublished material.

GENERAL EXAMPLE OF OPERATING COSTS OF FK (HOT EXTRUSION)

To produce FKs, costs include infrastructure, raw materials, energy and staff. Figure 39[62] shows the main costs associated with FK production by hot extrusion at a capacity of 1000kg/h. (A more detailed description of the individual costs related to an example FK production can be found in Annex 4.) These numbers can differ depending on equipment used, energy etc.

About 80% of production costs are for raw materials: rice flour, micronutrient premix and emulsifier. The cost of rice flour varies greatly, depending on whether it is purchased on the market or through vertical integration as a by-product from a rice mill. Also, micronutrient composition in the fortificant mix influences FK cost.

Energy accounts for about 12% of production costs. The lowest costs are those associated with personnel, quality control and other administrative activities. These costs, as in the case of energy, are heavily dependent on the location of the manufacturing plant. Furthermore, the degree of automation needs to be considered, since automation incurs high investment costs, but requires fewer personnel.

Investment related to infrastructure (new or redesigned plant) is usually a loan which is paid back over a five- to 12-year period. As such, allocation for annual interest payments needs to be considered. In China, for example, investment associated with infrastructure for FK production plants with Bühler equipment (1000 kg/h production output), amounts to approximately 6% of the total annual production costs.

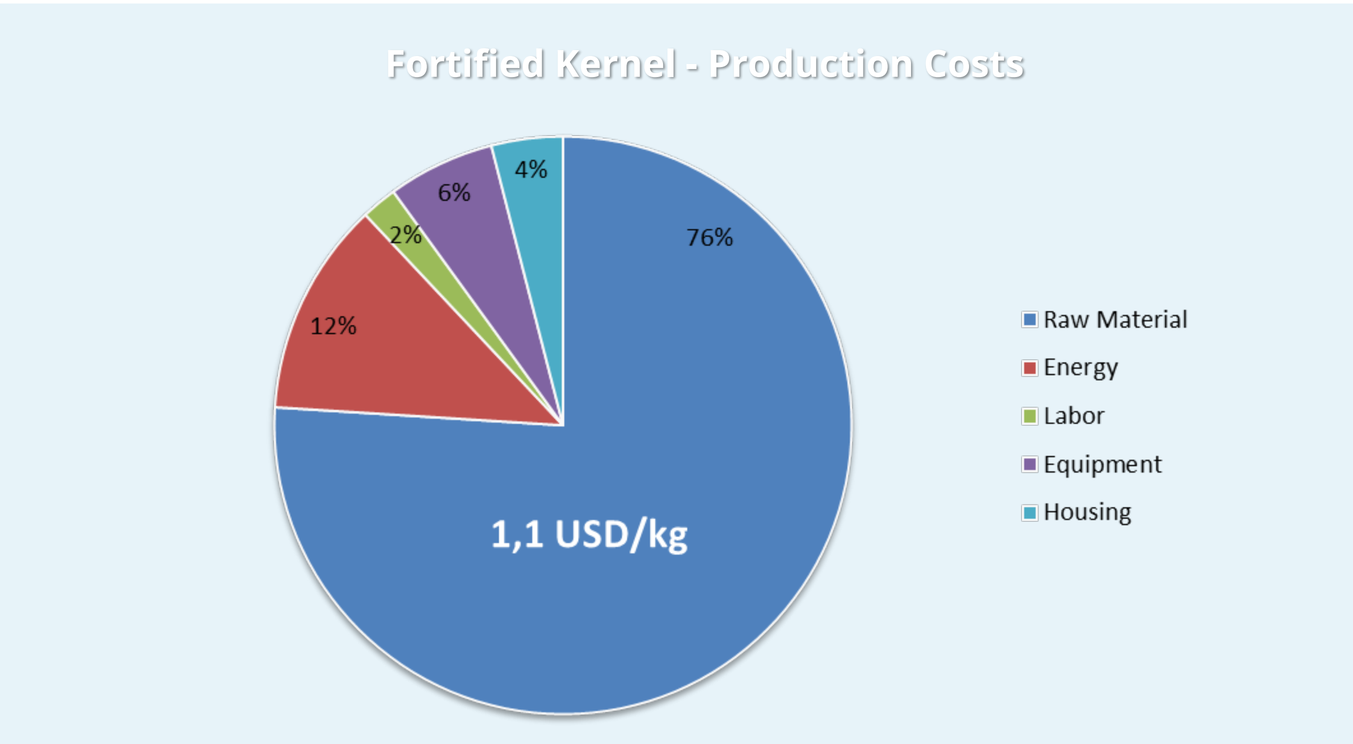


Figure 39: Example of costs for FK production (hot extrusion ~1000kg/h)

62 Bühler A.G., Aug 2018: Buhler Solution of Rice Fortification.

Annexes

ANNEX 1. SUGGESTED SUMMARY OF STANDARD OPERATION PROCESSES AND CHECKLISTS NEEDED FOR FK PRODUCTION WITH MANUAL OR SEMI-AUTOMATED WARM EXTRUSION LINES

Step	Action	Documents (SOPs)
Secure raw materials.	Check raw materials are available in sufficient quantity and quality.	Quality and safety tested and documented.
Rice flour preparation.	Cleaning, grinding and sifting of the rice raw material is sufficiently carried out before production starts.	Establish a granulation curve before process. Check granulation by sifting.
Ingredient preparation.	Preparation of micronutrient premix portions as per recipe per batch. Preparation of other ingredient portions, i.e. emulsifier.	Formulation total and per batch.
Preparation of extrusion line before start of production.	Check hygiene status of: mixer, auger, dosing, preconditioner; extruder – inlet, screw, die, cutter, transport devices, dryers. Assemble all components: insert screw, die plate, cutter, transport devices. Check availability of steam and hot water.	Notes on production data sheet (see Annex 3).
Pre-start all equipment components.	Start with the equipment that takes the longest time to reach the set point. Heat the dryers to the set points. Heat extruder barrels to the set points. Check proper function of each component individually: mixer, conveyor, dosing, preconditioner, extruder, transport devices and dryers.	Checklists.
Start mixing recipe per batch.	Pour flour into the mixer, add the micronutrient premix and the other ingredients (such as emulsifier). Start mixer for standard mixing time, then start adding hot water according to the recipe; keep mixing for the standard mixing time.	Note on production data sheet. See checklist and note.
Start preconditioner	Start preconditioner and heat up to the setpoint by steam addition.	Checklist
Transfer the dough to the dosing and start dosing into preconditioner.	Start with preconditioner outlet on bypass to check flour premix status manually. Without bypass, the extruder has to be started at this time.	Check manually for the right sensory properties (shown during start up by commissioning crew).
Start extruder	Check extruder and cutter revolution per minute setpoints for standard process and start water addition as per recipe when installed.	Checklist
Start FK production	Move flour bypass towards the extruder inlet. Monitor the motor load (KW or Amp), pressure, product temperature (when installed) for a standard production start procedure.	Checklist

Step	Action	Documents (SOPs)
Production control	Check ongoing FK specified parameters and adjust extrusion parameters as needed. For example, check the diameter of the FK and adjust the cutter speed or increase temperature or the residence time in the dryer when the moisture content is too high. In the case of lack of measuring tools like product temperature, SME etc. it is only possible to judge FK at end of the production line.	Note the process parameters in the production data sheet and compare to the standards.
Packaging / Storage	When the FK is approved to standard quality parameters and close to room temperature, start packing into defined bags and add product label with information, such as product, micronutrient content, kg, production date, lot number, etc.	Defined product label.

ANNEX 2. OPTIONAL DATA SHEET TO CHECK THE EXTRUSION PROCESS / PRODUCTION

FK production

Date: **Time:** **Charge / Lot:**

Parameters

	Standard	Observation / Signs
1. Raw materials	Lot. / Approved	
Rice flour		
Vitamin / Mineral premix		
Emulsifier		
...		
2. Equipment		
Hygienic status before production	Clean	
Dosing: Volumetric / Gravimetric	Volumetric	
Diameter of screw [mm]	105	
Screw speed [rpm]	850	
Extruder Screw Parameter:		
Diameter of screw [mm]	85	
Maximum screw speed [rpm]	720	
Maximum power [KW]	85	
Screw length [mm]	1500	
Die type (when different available)	Type A	
Preconditioner	Yes	
3. Process		
Rice flour	Kg/batch	
Vitamin / Mineral premix	Kg/batch	Note formulation total and per batch
Emulsifier	Kg/batch	
Production Parameters:		
Mass flow: feeding screw [kg/h, rpm or %]	400	
Water addition [kg/h or %]	68	
Steam addition [kg/h, % or valve scale]	36	
Screw speed [rpm]	720	
Motor power [KW]	30	
SME (motor power [KW]/mass flow [kg/h]*1000) [Wh/kg]	75	

Parameters

	Standard	Observation / Signs
Temperature Barrel 1 [°C]	90	
Temperature Barrel 2 [°C]	90	
… (regarding installation)	80	
Product temperature 1 [°C]	60	
Product temperature 2 [°C]	80	
… (regarding installation)	95	
Cutter speed [rpm or %]	2000	
Dryer belt speed [min or %]	30	
Dryer temperature section 1 [°C]		
Dryer temperature section 1 [°C]		

4. Product:

Product Name	FK	
Product Type	Natural	
Vitamin/mineral premix content by addition [%]	3	
Moisture content [%]	12	
Size & Shape: (average of X Kernels)		
Length [mm / CV]	4,9 / 1	
Width [mm / CV]	2,9 / 1	
Height [mm / CV]	2,0 / 1	
Package specification:	3 layer craft paper bag, LDPE layer in the corrugated inside, thickness = 90-100 micron	
Packaging [kg]	25	

5. Final Observation

Moisture content after extrusion	17%	
Finished Goods Moisture Content after drying	12,5%	
Control of granular size, size distribution	*As close as possible…*	
Control of colour and translucency	*As close as possible…*	
Cooking test—loss of materials [%]	10	

ANNEX 3. EQUIPMENT CHECKLIST

Equipment	Type/Name	Capacity/Amount	Notes
Raw material Handling			
Sifter			
Destoner			
Magnet			
Colour sorting			
Brown rice polishing			
Mill			
Sifter			
Blender			
Extrusion System			
Dosing gravimetric / volumetric			
Preconditioner			
Steam addition			
Water addition			
Extruder diameter/length			
Water addition			
Barrel heating cooling			
Screw configuration fix or adjustable			
Venting / Vacuum			
Die plate / Dimensions			
Cutter – blades fix or adjustable			
Barrel heating			
Barrel cooling			
Downstream equipment			
Transfer			
Dryer – 1 step, 2 or 3 step			
Dryer types			
Cooling			
Energy for drying			
Sifter			
Control - Automation			
Temperature sensors barrel or product			
Pressure sensor			
Control PLC			
Parameter and recipe management			
Visualization			
Trend logging and data storage			
Parameter limit settings and warnings			

Equipment	Type/Name	Capacity/Amount	Notes
Total capacity			
Investment			
Cost per ton FK			
Operators			
Energy			
Investment – interest rates			
Analytics			
Safety aspects			

ANNEX 4. EXAMPLE OF OPERATING COSTS FOR HOT EXTRUDED FORTIFIED KERNELS (1000KG/H)

costs per ton FK (USD)			**1'104**			
hours of production per year			**7200**			
extruder capacity tons per hour			**1**			
production of tons per year			**7200**			
				USD/year	**USD/t**	**% share**
costs of raw material	**t/h**	**USD/t**				
	0.95	350	Broken rice	2'394'000		30.1
	0.01	2500	Emulsifier	180'000		2.3
	0.04	12000	Vitamins/ Minerals	3'456'000		43.5
	1		**sum per year**	**6'030'000**	**838**	**75.8**
costs for investment of equipment and building						
	Equipment	3'000'000	USD			
	Building	1'500'000	USD			
	Amortisation time equipment	10	Years	300'000		3,8
	Amortisation time equipment	10	Years	150'000		1,9
	Interest	8	%	360'000		4,5
			sum per year	**810'000**	**113**	**10.2**
energy costs						
Electrical	Steam	0.04	USD/KWh			
	Electricity	0.15	USD/KWh			
	Steam consumption	15120000	KWh/year			
	Electricity consumption	2'160'000	KWh/year			
	Steam costs			604'800	84	7.6
	Electricity costs			324'000	45	4.1
			sum per year	**928'800**	**129**	**11.7**
wear, utilities and maintenance costs						
	equipment	10000	USD/year			
	parts	10000	USD/year			
	work	6500	USD/year			
			sum per year	**26'500**	**4**	**0.3**
personnel costs	amount per shift	shift				
production/quality	1	3	chief operators	86'400		1.1
	1	3	operators	64'800		0.8
sales/administration	0.2	1	office	4'320		0.1
			sum per year	**155'520**	**22**	**2.0**
			total costs per ton	**USD**	**1104**	**100.0**

ANNEX 5. EXAMPLE OF TWO WARM EXTRUDED FKS (A AND B) AND A HOT EXTRUDED FK (C)

Two FK products from warm extrusion process (A and B) and a product made by hot extrusion (C) were compared to illustrate differences in quality – as shown in Figure 40[63].

Product WE-A (300-400kg/h)	Product WE-B (75-100kg/h)	Product Bühler (300-400kg/h)
Appearance of the FK 		
Size distribution of FK (min + max) 		
Appearance of cooked FK 		
Appearance of drained cooking water 		
Weight of cooked FK (g): 54.6 Weight of drained cooking water (g): 260.9 Dry substance of rest water (%): **4.1** Loss of FK mass into water (%): **36.0**	Weight of cooked FK (g): 100.7 Weight of rest water (g): 208.3 Dry substance of rest water (%): **1.7** Loss of FK into water (%): **11.7**	Weight of cooked FK (g): 92.1 Weight of rest water (g): 201.3 Dry substance of rest water (%): **1.0** Loss of FK into water (%): **6.9**

63 Dr. T. Brümmer: unpublished material.

At first glance, the appearance of product A seems acceptable due to a certain transparency of the FK that seems comparable to rice, even if the product looks a bit darker than FK product B. The slightly darker colour could be related to the use of parboiled rice flour as the raw ingredient. However, upon closer observation, the size distribution of A is considerably less homogeneous than of product B. The largest kernels of product A are at least twice as big as the smallest ones. The differences in the kernels size are primarily caused by the construction of the nozzle plate and the head space in the extruder from the end of the screw to the die plate (see Cutter on page 41). The production plant of product A has a considerably higher throughput than B, which exacerbates the poor distribution of the dough flow on the individual die holes.

Product A's appearance also looks substandard after cooking. The product is slimy, and dissolves into the main matrix, as the figure shows. The reasons behind this could lie in an insufficient degree of cooking of the starch, the use of parboiled rice flour, the presence of dextrin in the premix, and lack of an emulsifier. Additionally, the conditions of preconditioning and the screw design in the process do not match, namely the screw needs to add more shear into the dough, as steam was added in the preconditioner. Conversely, product B process runs without steam. Thus, the extruder screw must introduce a significant amount of shear energy, even if the flour is preconditioned. This also might negatively affect the product final appearance. Unfortunately, the screws of these warm extrusion equipment have a fixed design, with only a conveying function and they cannot be adjusted if necessary.

A simple test to determine the quality of kernel might be a cooking test. This test can be used to check the stability of the kernels during cooking. It is recommended to carry out such tests before issuing a contract with an equipment supplier, as unstable kernels cause micronutrient losses. This is a significant quality issue that should be avoided.

In this test, 30 g of FK was added to 400 g of boiling water, and cooking time was set to 10 minutes. After cooking, FKs were emptied into a sieve and the drained water was collected (1 minute dripping time). The drained water and the remaining FK were weighed to calculate the losses of FK during cooking from the solids in the drained water. To do this, a certain amount of the drained water was dried at 90°C to constant weight (~12-14h overnight). The residue after drying, which is equivalent to the mass washed out of the FK, was weighed.

The lower the mass content, the more stable FKs behave during cooking, and the fewer micronutrients leach out into the cooking water. Furthermore, the micronutrients remaining in the kernels are thought to be better protected against damage from oxygen or light. Figure 40 highlights the very different characteristics related to mass loss during the cooking process in three products. Product A shows a loss of 36%, which suggests extremely high loss and thus an extremely reduced FK quality. Product B loss is slightly more moderate at 11.7%. The lowest loss occurs in product C (6.9%), which is hot extruded.

Glossary

Blending	Mixing of milled, non-fortified rice with fortified kernels in ratios between 0.5% and 2% to produce fortified rice.
Coating	Technology to make fortified kernels. Rice kernels are coated with a fortificant mix plus ingredients such as waxes and gums. The micronutrients are sprayed onto the rice grain's surface. The coated rice kernels are blended with non-fortified rice in a ratio between 0.5% and 2%.
Denaturation	Technology to make fortified rice. Polished milled rice kernels are dusted with a fortificant mix in powder form. This technology is only used in the United States and does not allow for washing, pre-cooking or cooking in excess water, since this will wash out the micronutrients.
Dosing	The addition of material in measured quantities.
Dusting	Technology to make fortified rice. Polished milled rice kernels are dusted with a fortificant mix in powder form. This technology is only used in the United States and does not allow for washing, pre-cooking or cooking in excess water, since this will wash out the micronutrients.
Extrusion	The continuous thermo-mechanical production process which combines the mixing and cooking of raw materials to result (in this case) in a product resembling rice kernels.
Fortification	Practice of deliberately increasing the content of essential micronutrient(s), i.e., vitamins and minerals, in a food, so as to improve the nutritional quality of the food supply and provide a public health benefit with minimal risk to health. The essential micronutrients are added to make the food more nutritious post-harvesting.
Fortified kernel	Fortified rice-shaped kernels containing the fortificant mix (extrusion) or whole rice kernels coated with a fortificant mix (coating). Fortified kernels are blended with non-fortified rice in a ratio between 0.5% and 2% to produce fortified rice.
Fortified rice	Rice fortified with fortificant mix by dusting, or non-fortified rice combined with the fortified kernels in a 0.5%–2% ratio. Typically, fortified kernels are blended with non-fortified rice in 1:100 (1%) ratio.
Gelatinization	The process by which starch granules in the presence of water and heat change from their crystalline form, to swell and take up water creating a 'cooked' product. This irreversible process is specific to each starch type.
Gravimetric	Measurement by weight.
Milled rice	Rice without the outer layers of hull, bran and germ; also called polished rice. Most of the rice's naturally occurring nutrients are in the layers that are removed.
Pitch	The distance between adjacent helical sections of the screw.
Regulatory monitoring	Comprises both internal and external monitoring; referred to as commercial monitoring at the retail level. The primary aim of regulatory monitoring is to ensure that the fortified foods meet the nutrient, quality and safety standards set prior to program implementation. Once regulatory monitoring has demonstrated that the program is operating in a satisfactory manner, evaluation of the program can be undertaken to assess its health impact.
Volumetric	Measurement by volume.

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Acronyms

FK	Fortified Kernel
PLC	Plant Programmable Logic Controller
SME	Specific Mechanical Energy
SOP	Standard Operation Process
WFP	World Food Programme

World Food Programme

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