INNOVATIVE FOOD TECHNOLOGIES FOR REDISTRIBUTED MANUFACTURING

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Synopsis

This report aims to provide an overview of food technologies that could support the wider adoption and application of Re-Distributed Manufacturing (RDM) in the food sector, and has been developed as part of a series of feasibility studies under the umbrella of the ‘Food, Energy and Water Local Nexus Network’ (LNN) for RDM. The technologies include both traditional food processing technologies that could be reconfigured to be used in smaller scale and also a number of new emerging food technologies that currently may have limited commercial applications, but could provide significant potential in the context of RDM. These technologies are assessed against fourteen specifically defined criteria in order to identify their benefits and drawbacks for future applications of RDM.

One of the main findings of this study has been that RDM, as an innovative production structure, necessitates further research, innovation and development (RID) in order to enable successful applications by food businesses. These RID activities could be categorised under three areas of process level, product level and system level innovations. In this context, a number of key research questions regarding future development of food technologies for small scale production systems are presented. Based on these, the report also presents a number of specific research challenges that need to be addressed in order to develop a viable and sustainable approach to the production of food products on smaller scales (redistributed) and closer to the source of consumption (localised), whilst preserving the safety and maintaining the quality of manufactured food.

Finally, one of the main conclusions of this study is that increasing productivity, improving resilience and reducing waste are important considerations upon which the future of the UK food sector must be founded, and distributed manufacturing of our food products will play a vital role in the achievement of these goals.

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1. Introduction

The food manufacturing industry seeks continuous improvements in most of its activities in order to not only increase profitability, but also to provide consumers with better products that can satisfy their changing needs. Traditional competitive measures implemented by food organisations have focussed specifically on three key performance indicators: productivity, innovation and quality. By developing strategies which could improve any of these three business indicators, food manufacturers have been able to grow and create more valuable food products for consumers. However, the food sector is now facing increased pressure from governments and consumers to improve the sustainability of their products, production processes, supply chain activities and business strategies. Consequently innovative approaches that can provide the industry with meaningful and significant improvements are being explored due to the ever-increasing need to adapt and change in order to remain competitive. In this context, the concept of Re-Distributed Manufacturing (RDM) has been identified as an emerging organisational theory that can support the food industry in its upcoming and future challenges.

This report has been developed as part of a series of feasibility studies under the umbrella of the *'Food, Energy and Water Local Nexus Network (LNN) for RDM',* funded by the Engineering and Physical Science Research Council (EPSRC) and Economic and Social Research Council (ESRC), which started in early 2015. The LNN focuses on the development of local nexuses of food manufacturing with considerations for energy and water supply. Studies of these connections present opportunities for improving resource utilisation, production, and consumption to meet requirements for food products and services within a local context. These studies could also contribute to the shared prosperity between business and community, and between human society and natural ecosystems. The achievement of these goals clearly necessitates a complex and significant transition, which requires "smart" engineering (smaller scale technologies, integrated processes), and driving forces from businesses, communities and policy makers.

1.1. Goal, scope and structure of the report

The report aims to provide an overview of the concept of RDM in the context of food manufacturing, considering the enabling innovation required at the three different process, product and system levels. Figure 1 illustrates what is commonly considered the main components of a food technology, which not only includes traditional processing equipment, but also refers to the science and the actual system of enabling the production of a food product. The special focus of this study is the role of modern innovative food processing technologies in supporting RDM applications and management in the future. The report contains an overview of a number of food technologies with relevant potential for RDM applications, and a brief analysis of their technological suitability against a set of predefined criteria.

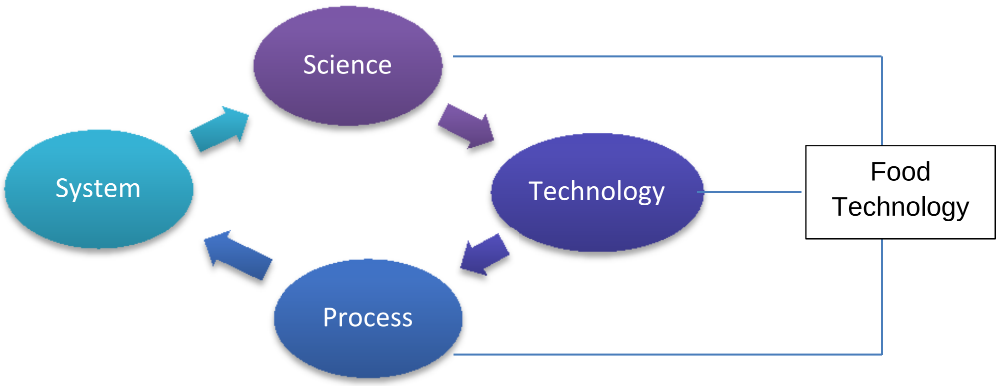


Figure 1. Food technology links

The report concludes with a set of potential research and innovation challenges related to these food technologies to successfully incorporate redistributed and localised approaches as viable future manufacturing strategies for the UK food industry. Figure 2 illustrates the overall structure of the report which is divided into five major sections. The first section of the report includes a brief background and a simple definition for the concept of RDM, alongside some of the expected benefits to be obtained and the drivers for its adoption. The second section presents an overview of three different focus areas: product, process and system, and how it is expected that future innovation in these areas will influence and support RDM development. The third section focuses specifically on the food processing technologies that can be used in RDM applications with their potential impacts and some of the barriers that need to be overcome to enable such potential to be realised. The final two sections present a number of RDM research questions and challenges in the context of food manufacturing together with some recommendations for future work.

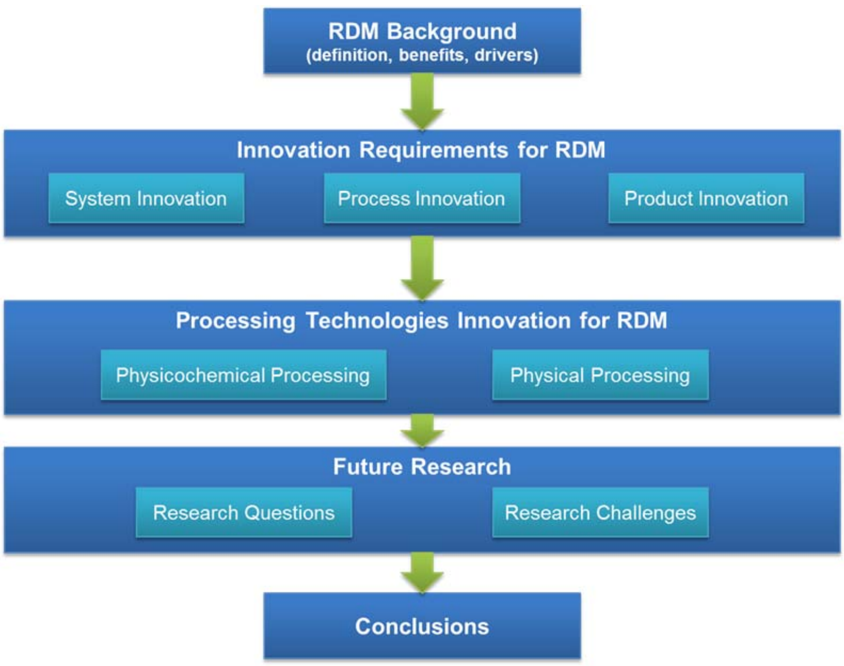


Figure 2. Report structure

2. RDM Background

The concept of 'Redistributed Manufacturing' does not have a standard and widely accepted definition. The hypothesis of changing the way UK manufacturing is organised was introduced during a workshop held by the EPSRC and the ESRC research councils in November 2013. During this event, an initial definition of RDM emerged as:

> *"a way of encompassing technology, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location and scale."*

Understanding the ways in which RDM will affect manufacturing industries prior to its actual implementation is of vital importance. Table 1 [1] summarises a number of the research and innovation areas which should be considered under the umbrella of RDM together with their specific impacts in the UK manufacturing context.

Table 1. RDM for UK manufacturing

Research & Innovation Areas	Impacts on UK Manufacturing
- Localised manufacturing - Flexible manufacturing - Resilient manufacturing - Sustainable and resource efficient manufacturing - Reconfigurable and replicable manufacturing	✓ Changes in labour and production. ✓ Technological, chemical and mechanical advances. ✓ New regulations and business models. ✓ Political and economic implications.

RDM may neccesitate changes to incumbent business models and supply chains by generating new trends and opportunities. In certain cases, it may complement existing practices and assist current manufacturing business; in others, it may require new thinking to unlock the potential for improving efficiency based on concepts and ideas derived from RDM developments. Figure 3 [1] shows several elements and characteristics that could be affected by RDM.

Figure 3. RDM workshop word cloud

2.1. Benefits and drivers for RDM implementations

A key challenge in the implementation of RDM is identification and measurement of its potential benefits. Figure 4 shows some initial benefits associated with the adoption of RDM. These benefits may have varying impacts for different food products and within various food supply chains.

In recent years, the sustainability and resilience of food manufacturing have become vital considerations due to various regulatory pressures, consumer demands and reduced availability and accessibility of resources due to climatic constraints. In this context, RDM environmental benefits such as reduction in transportation, storage and refrigeration requirements, and increased shelf life due to producing food products closer to the point of consumption are commonly reported. Moreover, food manufacturers have identified economic benefits associated with production flexibility offered through RDM as fundamental requirements for improved productivity and the ability to react to consumers' demand for food customisation and/or personalisation. It should also be noted that in addition to these environmental and economic benefits, implementation of RDM often results in a number of social and/or societal benefits, such as creation of local jobs, sustainable growth of local/regional economy and reduction in transportation and movement of people together with the associated work satisfaction.

Figure 5 depicts a wider range of the benefits and drivers in support of RDM implementation, which are explained in more detail below:

- **Raw materials optimisation**: through local provision and use of raw material and effective management of waste associated with supply and production.
- **Efficient demand fulfilment**: reducing the distance (hence time) between manufacture and consumption of a food product leads to more effective management of consumer/market, reduces inefficiencies in the supply chain and increases customer satisfaction.

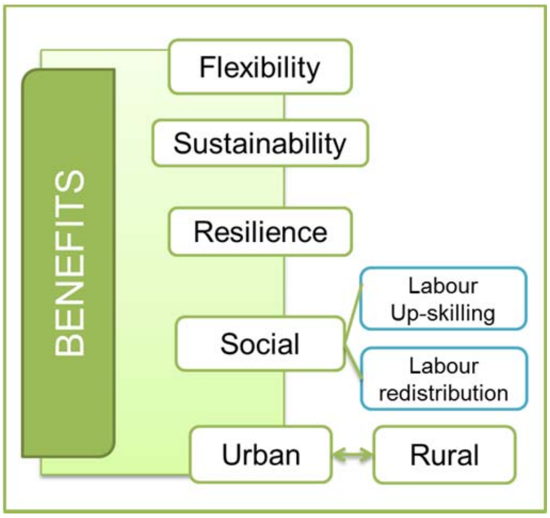


Figure 4. RDM expected benefits

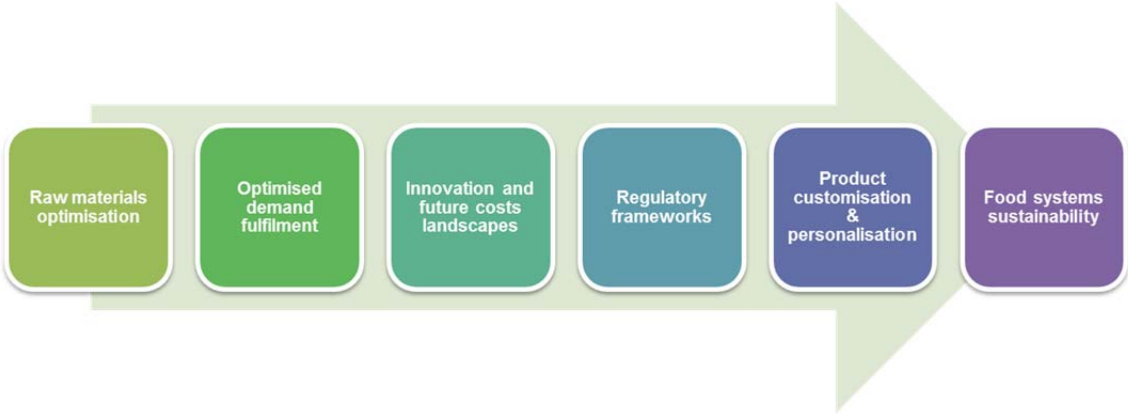


Figure 5. RDM implementation drivers

- **Future costs/pricing landscapes**: identifying new competitive advantages, improving productivity and diversifying cost efficiency measures are of paramount importance for the long-term viability of any food business.
- **Regulatory Requirements**: are playing an increasing role in decisions on future investment, operational planning and control of food manufacturing companies.
- **Product customisation & personalisation**: proximity to markets could make it easier to achieve greater customisation and personalisation of food products due to better understanding and faster response to consumer needs. Increasing demand for niche products, artisan and healthy foods could be more readily addressed with distributed production systems.
- **Food security and traceability**: reported misuse of ingredients in food products, increased attention and demand regarding animal welfare, and rapid growth of the market for organic food are indicative of increased pressures for improved food quality, security and traceability.
- **Energy-water nexus**: availability and accessibility of energy and water are increasingly becoming two key drivers in many manufacturing decisions such as selection of locations for production facilities, process reengineering and improvements, optimisation of planning and management activities and many more. The infrastructure support, in particular with regards to energy and water limitations, are hindering the growth plan for large-scale centralised manufacturing facilities whereas such demand could be more evenly distributed using an RDM approach.
- **Long-term sustainability of food systems**: population growth, changes in dietary behaviours/requirements, loss of arable land, climate change, and depletion of natural resources urgently demand a need to alter the way we grow, manufacture and consume our food products. Reducing waste, and improving resilience and sustainability are important considerations upon which the future of the food sector must be founded.

3. Process, Product and System Innovation

Redistributed manufacturing, as an innovative production structure, necessitates further research, innovation and development (RID) in order to enable successful applications by food businesses. These RID activities could be categorised under three areas of process level, product level and system level innovations. This report is mainly focused on the process innovation aspect; however, this section aims to provide a brief overview of the essential interactions between these three RID areas to support wide-scale implementation of RDM within food industry applications. Figure 6 highlights in Ven diagram style some of these RID activities, which are further discussed below.

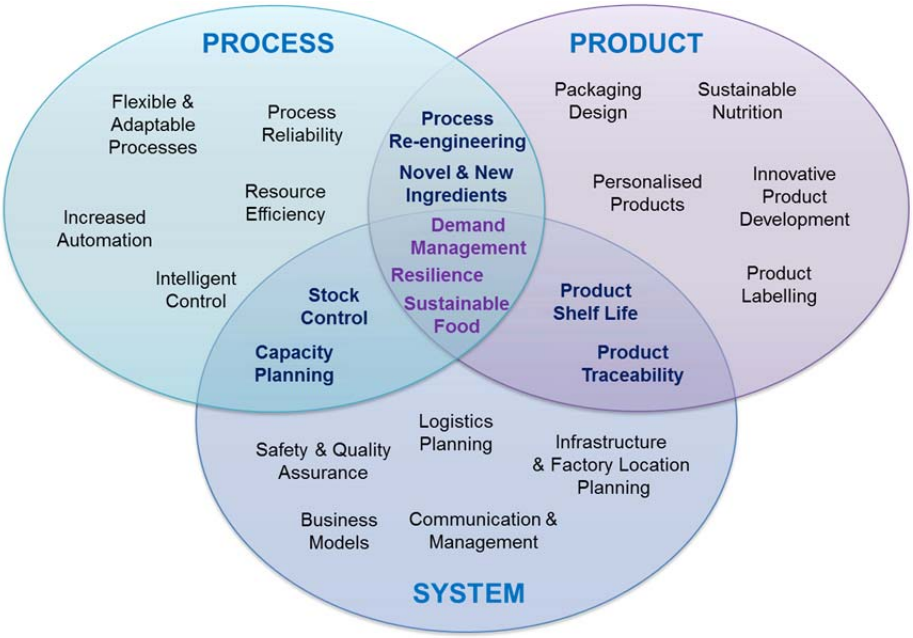


Figure 6. Ven diagram on process-product-system innovations

3.1. Process innovation

One of the main expectations from manufacturing processes within an RDM model is the flexibility to produce products in the right quantity, needed quality, at the right time and location. Such RDM production processes must also be able to adapt to "non-standard" raw materials and ingredients which will be supplied by more widespread suppliers. Moreover, these processes will need to be reconfigurable to deal with evolution in consumer demand without requiring major changes in production lines. On the other hand, RDM process innovation must bring about increased automation in order to have similar productivity to centralised systems while offering the required quality. In addition, innovation in 'intelligent process control systems' will be necessary to effectively manage and optimise production activities within distributed manufacturing facilities. Such intelligent and responsive control of processes will be vital to react quickly to changes in product demand and other systems constraints.

While the existing large-scale centralised food manufacturing systems deal with reliability issues through practices such as overstock and inclusion of redundant processing lines, RDM processes must be very reliable in order to deal with the more dynamic nature of local markets and consumer demands. Achieving a similar level of resource efficiency is another key challenge for RDM processes, as this has been addressed through ‘economy of scale’ within large centralised food manufacturing systems. Food technologies which can improve resource usage and provide better utilisation of ingredients will be key enablers of RDM implementation.

3.2. Product innovation

Modern food manufacturers must possess the ability to continuously develop and introduce new products to address forever increasing and changing consumer demands and to remain competitive. In this context, product innovation has become a key enabler to support food businesses. Evolution in product demand has been driven by changes in population demographics, dietary requirements and health and safety issues (due to non-communicable diseases and allergies). Therefore the wide scale implementation of RDM will require innovative product development techniques capable of offering highly customised and personalised products. Another key consideration in this area is the need for sustainable nutrition for which manufacturers will have to produce their products with the available non-standard raw materials and ingredients (e.g. protein from insects; vitamins and minerals from algae) which, if successfully adopted, could unlock numerous opportunities.

3.3. System innovation

Systems engineering plays a key role in successful implementation of RDM in the food industry, and this inherently requires novel, often more complex multi agent systems due to its different operational nature compared to traditional large-scale centralised manufacturing systems. Systems innovation is expected to be able to drive the changes towards distributed manufacturing systems in an efficient way so these new structures can be competitive. As an example of systems innovation, future distributed food manufacturing systems will demand robust supply chain management and operational tools which will need to be able to cope with even greater complexities in distributed planning and control of production activities. In addition, innovative business models which can optimise food manufacturing systems will be required in order to successfully develop distributed production systems capable of working smoothly and providing greater benefits than existing large-scale centralised systems. In this context, system adaptability to local market opportunities will be essential for unlocking a wider range of potential benefits.

3.4. Common factors in future food innovations

Figure 6 also highlights that there are several factors which are expected to influence future RID requirements in two or more of process, product and systems levels, some of which are outlined below.

3.4.1. Common factors influencing process and product innovation

- **Novel & new ingredients**: Innovations in ingredients and product development could lead to more productive processes to support RDM implementations.
- **Process re-engineering**: process and product innovations will require close integration to ensure synergy and improvement. Customised and personalised products will require processing capabilities and flexibilities in order to be able to respond quickly and efficiently to consumer demand.

3.4.2. Common factors influencing process and system innovation

- **Stock control**: innovations in the area of inventory management and stock control will be required since changing the food supply chains will challenge manufacturers’ production and inventory management. Seasonal ingredients and raw materials may no longer be available off-season, and inventory management together with process innovation will have to address this issue in order to enable the provision of food products for consumers with the same quality and composition throughout the year.
- **Capacity planning**: systems and processes innovations need to consider capacity planning in order to optimise the availability of products within various local markets. Moreover, processing times and production schedules need to be optimised to reach similar production rates currently achieved by centralised systems.

3.4.3. Common factors influencing process, product and system innovations

- **Demand management**: innovative demand management tools and techniques will be required to cope with the more complex challenge of producing a large variety of products in the right quantity, needed quality, at the right time and location.
- **Improved resilience**: RDM food systems are expected to offer greater resilience levels due to shorter supply chains that are simpler to manage and less susceptible to disturbances. However, this requires RID across all three areas of process, product and system.
- **Sustainable food**: innovations in products, processes and systems could achieve radical improvements in the overall sustainability of the food sector. RDM is expected to provide a wide range of environmental, economic and social benefits, as outlined in Section 2.

4. Food Technologies to Support RDM

This section of the report focuses on assessing the suitability of a number of food technologies for future developments of distributed food production systems. Existing literature does not provide a standard classification for different food technologies, and therefore Table 2 has been devised to offer a simple overview of processes and technologies that are utilised by various food manufacturing applications. The goal is to show the different umbrellas under which food technologies can be classified and assessed for their applicability in future distributed food manufacturing businesses.

The main differentiation commonly referred to in the literature about food technologies is ‘traditional’ versus ‘novel’ technologies, i.e. available technologies with past historical use in food manufacturing operations in a standard processing style versus innovative processing technologies which are often under development with limited wide-scale applications. Such differentiation is important for RDM due to the fact that in some cases recent developments might serve as enablers for implementing change, while in other cases, the utilisation of traditional technologies can directly support distribution of the production with no need for further innovations.

Traditional technologies, with the extensive efforts that have already been made in improving their performance, together with their enabling links to novel technologies, will still have a significant role to play in the future of distributed food manufacturing. Such technologies can be used for different purposes; they can be used only during the preparation stages of raw materials and ingredients for further processing (i.e. washing, cutting or baking) or to preserve the manufactured foods and extend their shelf life (i.e. canning, freezing and drying). Some traditional technologies can work both as product preparation and preservation technologies (e.g. pasteurisation which can be used to prepare milk for human consumption and also prevents the milk from spoiling).

On the other hand, when considering food technologies which have been recently generated and developed, it is important firstly to determine the feasibility of their application for commercial purposes before considering their suitability for RDM. Hence, in Table 2 novel food technologies are further divided into “applicable technologies” which are those with existing applications at an industrial level, or the “emerging technologies” referring to those which are either currently under further research and development or going through early stages of proof of concept or scaling up from laboratory processes.

Based on the consideration of RDM principles together with its barriers and drivers, twelve novel technologies were selected for special focus in this report (see Figure 7). These technologies were selected due to their significant potential as enablers for wide-scale implementation of distributed food manufacturing systems, and have been reviewed under the two headings of Physical and Physicochemical processing technologies.

Table 2. A classification of Technologies and Processes used in Food Manufacturing

	Processes & Technologies			
	Principle	Traditional	Novel	
			Applicable	Emerging
FOOD MANUFACTURING	Physical	Washing Cutting Mixing Forming [2]	Robotics [3] Extrusion [4] [5] Modified Atmospheres [6] Membrane Separation [7]	Additive Manufacturing [8] Nanotechnology [9] [10] Edible Coating [11] Membrane Emulsification [12] [13]
	Physicochemical	Frying Baking Boiling Blanching Thawing Fermentation Distillation Drying Pasteurisation Heat Sterilisation Chilling Freezing Others [2] [14]	Ohmic Heating [15] [16] Microwave Heating [17] [18] High Pressure Processing HPP [19] [20] [21] Irradiation [22] Ultrasound [23] [24] Pulsed Electric Fields [25] [26] Freeze Drying [27] Osmotic Dehydration [28] Spray Drying [29] Superheated Steam Drying [30]	UV & Pulsed Light [31] [32] Pulsed X-Rays [33] Cold Plasma [34] [35] Oscillating Magnetic Fields [36] Vacuum Cooling [37] High Pressure Freezing [38] Electric Arc Discharges [2] Microfluidics [39]

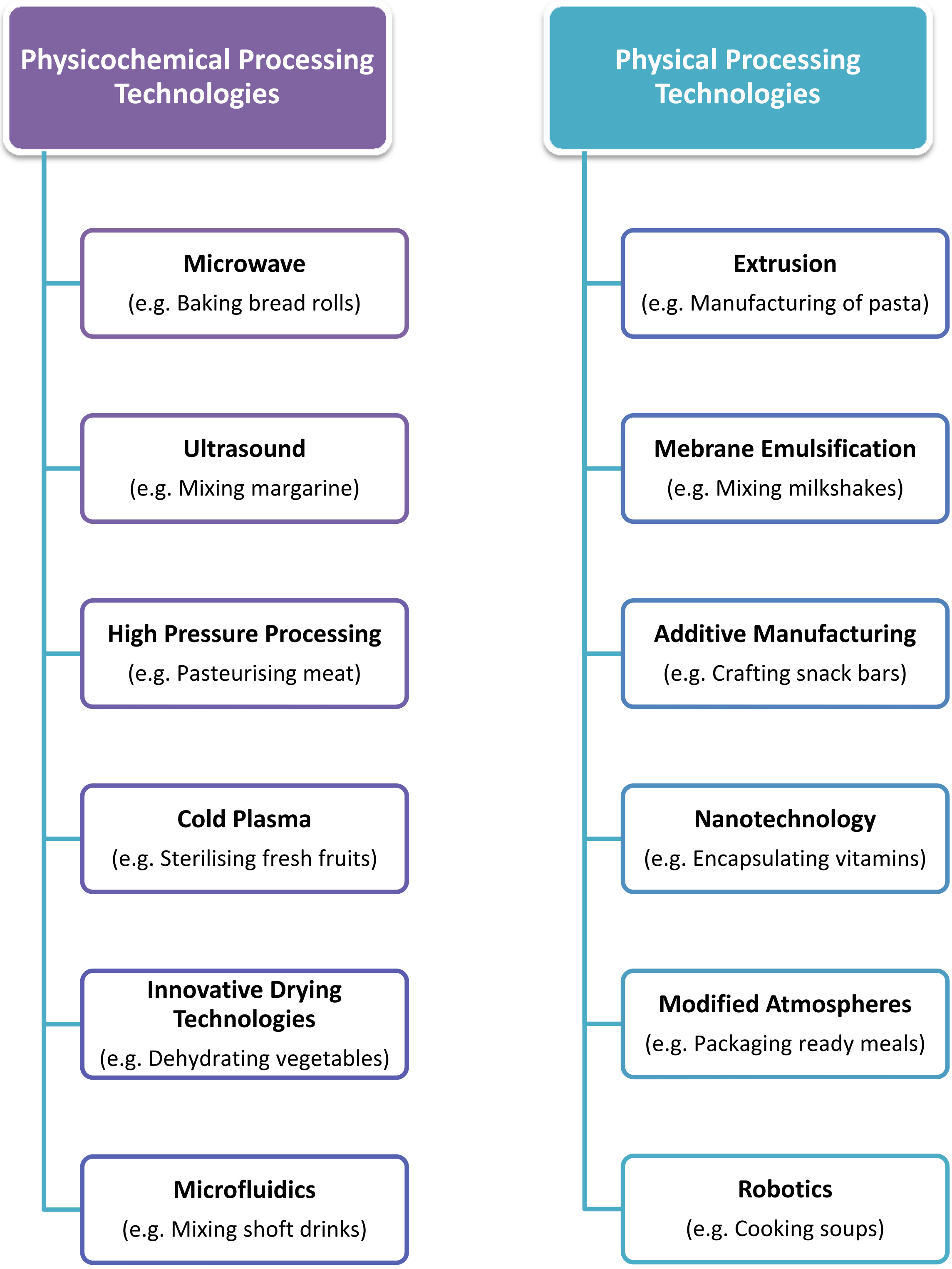


Figure 7. Selected Technologies

4.1. Re-distributed manufacturing assessment criteria

In order to assess the compatibility and suitability of the abovementioned food technologies for distributed food manufacturing, fourteen specific criteria have been defined (see Table 3). These criteria encompass a broad set of considerations, ranging from process design and operational issues to resource efficiency and cost effectiveness. In addition, for each RDM assessment criterion, some of the key issues together with an example consideration have been included in Table 4.

Table 3. Description of RDM assessment criteria

RDM Assessment Criteria	Description
Technology Maturity	Technology readiness level regarding its capability for utilisation in industrial facilities
Technology Scalability	Capacity to adapt to different production volumes while maintaining product quality and characteristics
Technology Flexibility	Process speed and production rate that can be carried out using the technology with minor adaptations
Product Customisation Potential	Capability of customising and changing product parameters to adapt them to specific needs
Nutrients and Sensory Impact	Nutritional values retention and structure preservation ability by the processing technology
Product Shelf Life Impact	Influence on the product shelf life which is a key constraint for many food products
Process Integration Potential	Inter-technology integration capabilities to generate complete production solutions
Product Quality Impact	Changes or effects on the final quality of the manufactured products
Throughput Capacity	Manufacturing efficiency of the technology in terms of speed, volume and productivity
Resource Efficiency	Sustainability in terms of energy, water and materials utilisation
Technology Safety	Operational safety of the technologies in industrial facilities regarding their risks and limitations
Capital Costs	Business investment requirement in order to implement the technology within a production facility
Operational Costs	Running costs once the technology is operational on the factory shop floor
Consumer Acceptance	Consumer willingness to buy and use the products produced with the specific technology

Table 4. Key Issues and example considerations for each RDM assessment criteria

RDM Assessment Criteria	Key Issues	Example Considerations
Technology Maturity	Reliability, repeatability, and adaptability for innovative products	3D printing of food products
Technology Scalability	Varying batch sizes and production volumes in smaller scale production	Extrusion of bespoke breakfast cereals or pasta products
Technology Flexibility	High variety, new product design, production system reconfiguration	Innovative drying process for diverse food products
Product Customisation Potential	Consumer demand and/or preference complexity, very small batch production, profitability	Nanotechnology enhanced products to meet specific local dietary requirements
Nutrients and Sensory Impact	Maintaining and provision of essential nutrients in small scale production	Ultrasound emulsification of margarine to enhanced nutritional content
Product Shelf Life Impact	Preservation, storage requirements, structural degradation control	Modified atmospheres packaging to reduce the need for preservatives
Process Integration Potential	Process design complexity, process chain compatibility	Application of nanotechnology in 3D printing of food products
Product Quality Impact	Food safety and hygiene, standardisation of food formulation, maintaining ingredient consistency	Robotic processing of non-standard food ingredients
Throughput Capacity	Production demand at local level, variation in market demand, seasonality of food products	Seasonal demand for snacks and ready meals linked to a special event, e.g. Olympics or Football World Cup
Resource Efficiency	Energy and water efficiency and/or food waste generation in small scale food production	Energy demand per product from innovative drying technologies
Technology Safety	Operational safety, emissions, noise.	Cold plasma sterilisation of localised vegetable produce
Capital Costs	Equipment and installation costs, factory space requirements	Application of ultrasound technology production of dairy products
Operational Costs	Labour requirements, set up costs, overheads, maintenance and repair costs	Personalised nanotechnology nutrients encapsulation
Consumer Acceptance	Preferences and perceptions of product variation, consumer tolerance for new food technologies	Use of microwave technology in bakery products

The significant complexity involved in moving from a large scale centralised approach to localised distributed food production necessitates a holistic multifaceted assessment of food technologies to analyse their suitability and viability. For example, a possible utilisation of microwave technology for baking different food products not only requires consideration of flexibility and scalability of the process, but also consumer acceptance and tolerance regarding this new method for processing baked products. Such wider understanding and analysis of consumer preferences and perceptions could directly influence the success or failure of this approach.

In order to distinguish between the suitability and viability of food technology, a scaling model (depicted in Table 5) is utilised. Table 5 shows the correlated assessment values and how these can be used to assess food technologies against each RDM assessments criteria. The reason for utilising such a simplified scoring model is the wide range of considerations and different possible weightings for the diverse RDM assessment criteria for a specific food application; more quantitative 'single score' models would have been subject to many assumptions and therefore would not be accurate, informative or descriptive of many practical complexities.

Table 5. Key for the assessment criteria values

Value	Key
○	No impact/benefit or concept development
◔	Low impact/benefit or basic development
◑	Medium impact/benefit or early stage development
◕	Substantial impact/benefit or fully developed
●	Significant impact/benefit or advanced development

4.2. Physicochemical processing technologies

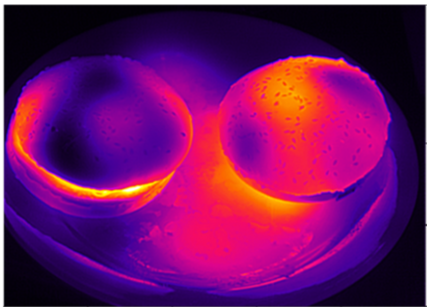
The physicochemical processing technologies reviewed in this report are considered minimal processing technologies which essentially aim to offer higher quality products in terms of flavour, structure and nutritional value by using less intensive and damaging processes while still offering the same final products in terms of features and taste. Furthermore, they aim to preserve functionality, and in some cases create new textures and extend the shelf life of food products. All of these characteristics make them potentially suitable for distributed food manufacturing, and this assumption is further explored in the following subsections with the aid of the RDM assessment criteria.

4.2.1. Microwave technology

Microwave technology is widespread in food manufacturing operations for heating, cooking and for enhancing other applications. The best known use of this technology is for home heating and cooking, but it is also used in various industrial operations and extensive developments have made it a well-known technology with numerous benefits for food manufacturers. Essentially microwave technology uses microwave energy, which is a form of electromagnetic radiation between 300 MHz and 300 GHz, and delivering it to food products in an enclosed cavity [17]. The microwaves cause vibrations of the product's water molecules and generate heat that can be controlled for different food processing applications.

Table 6 shows the predicted suitability of microwave technology for RDM using the abovementioned assessment criteria. The results of this analysis demonstrate the applicability of microwave technology for RDM. The high maturity level and the short processing time of microwave technologies can support distributed production systems which require well understood processing parameters and high speed production rates in order to reduce stock dependency and the time-to-market. Moreover scalability, capability for integration with other processes and consumer acceptance make microwaves an important technology for the optimisation of manufacturing systems in a less centralised system. Concerns regarding the availability of resources (in particular energy) in distributed structures could be reduced by utilising this technology. On the other hand, the low customisation capability that microwaves offer can be overcome by using it with other methods such as product formulation and adaptation of base materials from localised suppliers. These all highlight the potential that microwave technology could provide within extensive applications for multiple food manufacturing operations and a wide range of food products.

Table 6. Microwaves assessment in a distributed production system



Microwave Technology

Functionality: processing, product preservation, components extraction.

Novelty: reduced processing times, secondary processes enhancer.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
●	◕	◑	◔	◑	◕	◕	◕	●	◕	◑	◑	◕	◕

4.2.2. Ultrasound technology

Ultrasound technology is an innovative food technology which is still subject to extensive research to identify its full potential in food production. Ultrasound is defined as sound waves with frequencies above the threshold for human hearing (>16 kHz) and in its most basic definition, refers to pressure waves with a frequency of 20 kHz or more [23]. Several industrial processes utilise power ultrasound as a processing aid technology. The industrial applications of this technology range from mixing of materials, foam formation or destruction, agglomeration and precipitation of airborne powders; to the improvement in efficiency of filtration, drying and extraction techniques from solid materials and the enhanced extraction of valuable compounds from vegetables and food products.

The results of the analysis of the feasibility of utilising ultrasound technology in distributed food manufacturing systems are summarised in Table 7. These demonstrate that the good product quality, the reasonable processing times, and the flexibility of this technology for adaptation to changes in the processing line could facilitate and promote its utilisation in distributed food manufacturing systems. Moreover, current products on offer to consumers have shown good acceptance due to the desirable sensory characteristics and good nutrient content provided after processing with ultrasound. This could justify the future utilisation of ultrasound technology in a wider range of food products. It is expected that with the appropriate further developments, the implementation barriers which could detract from its growth, such as difficult customisation and high operating costs compared to other technologies, could be overcome. Ultrasound technology could compare favourably with existing processing technologies in profitability and productivity levels while additionally granting numerous benefits in terms of flexibility and increased shelf life of food products.

Table 7. Ultrasound assessment in a distributed production system

Ultrasound Technology

Functionality: processing, product and equipment sterilisation.

Novelty: structure generation, minimum impact on nutrients and sensory characteristics.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◑	◕	◕	○	●	◑	◕	◕	●	◑	◔	◕	○	●

4.2.3. High Pressure Processing technology

High-pressure (HPP) processing technology, also known as high hydrostatic pressure (HHP), or ultra-high pressure (UHP) processing, is a non-thermal food processing method utilised for liquid or solid foods with or without packaging [19]. This technology consists of placing the product to be treated in a pressurised vessel, which is then submerged in a liquid that is used for transmission of pressure in order to obtain the desired results. This innovative technology has been used to generate better quality products compared to other traditional heat related food processing technologies. HPP also offers the ability to enable sensory characteristics and nutritional value factors retention, which are becoming very important for food manufacturers in terms of quality.

The level of maturity together with the nutrient preservation and sensory properties (see Table 8) of this technology could assist with its implementation in distributed food manufacturing. Furthermore, the flexibility of this technology in terms of products that can be manufactured could reduce the key concern related to costs of duplicating processing equipment and segregation of production facilities in RDM applications. On the other hand, further research is needed to reduce operational costs to avoid the post-processing refrigeration requirement due to limited antimicrobial effects.

Taking into consideration that HPP can easily be integrated with other technologies and that further equipment development could reduce its cost, it can be concluded that HPP technology is a promising technology which could be used in distributed manufacturing systems, offering benefits to consumers and manufacturers not only in economic terms, but also with regards to numerous economic and social considerations.

Table 8. HPP assessment in a distributed production system

High Pressure Processing Technology

Functionality: processing, product preservation, structural changes.

Novelty: nutrient retention, reduced processing times, new structure generation.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
●	◑	◕	◑	◕	◔	◕	●	◑	◑	◑	○	◔	◑

4.2.4. Cold Plasma technology

Cold plasma technology is a preservation technology which can be used for decontamination and sterilisation of food products and other surfaces. It can be applied as low-pressure plasma inside a vessel, or as atmospheric plasma (e.g.: on conveyor belts) [34]. Its most important characteristic is the capability of reaching difficult areas that in some cases could not be treated with the utilisation of other technologies. The large scale industrial utilisation of this technology is currently limited which makes it difficult to assess its potential for implementation within distributed food production. Nevertheless, the short processing times, high yield throughput capacity, and the potential to be integrated with other technologies as a post-processing technology (see Table 9) could support its utilisation in RDM applications.

Cold plasma has also shown good capacity for the retention of nutrients and sensory characteristics due to the minimum impact that it causes on the treated elements. In addition, the capabilities for continuous or batch processing, and the ease of application to multiple food products could support its deployment in distributed food production facilities. On the other hand, the relatively low maturity, concerns regarding safety and current set up costs have impacted its wide scale adoption within food manufacturing. It is expected, as has been the case with other new innovative technologies that further development will lead to a reduction in required capital costs and risks derived from this technology. This could facilitate a widespread use of cold plasma for the sterilisation and shelf life extension of food products in small scale manufacturing.

Table 9. Cold plasma assessment in a distributed production system

Cold Plasma Technology

Functionality: product preservation, product sterilisation, superficial treatment with no heating requirement.

Novelty: low impact on product, continuous processing potential, innovative preservation technology.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◔	◑	◑	○	◑	◕	◕	◕	●	◕	◔	◔	◑	○

4.2.5. Innovative drying technologies

Dehydration is one of the most commonly used food processing operations, aimed at improving the preservation of foods by allowing extended periods of storage via reduction of the water activity in the ingredients and products. Moreover, by reducing water content in the products a reduction in weight can also be obtained which can generate reductions in transport and storage costs [40]. It is expected that future novel drying technologies will improve resource efficiency (such as energy requirements). Drying can cause deterioration of both the sensory quality and the nutritional value of foods; however, a number of innovative drying technologies, such as spray drying, superheated steam drying and freeze drying technologies, are seeking to minimise the undesirable changes. Spray drying technology is the generation of powders from products with high sugar content [29]. The superheated steam drying technology consists of vaporising the water inside the products through contact with superheated steam [30]. Freeze-drying technology consists of removing water or other solvents directly from a frozen product [27].

Table 10 shows the RDM assessment criteria for these drying technologies, which compared to other traditional drying technologies, offer product shelf life extension, high efficiency in resource usage and improved quality of products, making them very good candidates for utilisation in distributed food manufacturing. Drying technologies could also support the provision of small scale manufacturing of high quality stored ingredients with optimum retention of nutrients and sensory characteristics. Moreover, it is envisaged that such innovative dehydration processes will continue to be one of the key components of future food manufacturing and their important role in a distributed production system should not be neglected in order to enable the food industry success in creating a more sustainable future system.

Table 10. Innovative drying technologies assessment in a distributed production system

Innovative Drying Technologies

Functionality: product and ingredients preservation, new product development.

Novelty: minimisation of product damage, better structure retention, faster processing times.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◕	◑	◑	◔	◕	●	◑	◕	◑	◕	◑	◔	◑	◑

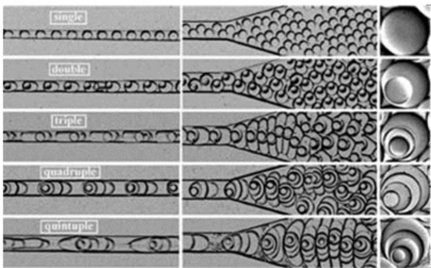
4.2.6. Microfluidics technologies

Microfluidics technology is a novel area of food research, and can be defined as the science which includes the design, manufacture and operation of different processes and devices or equipment that utilise minimal amounts of fluids in laminar regimes [39]. It has yet to be applied in large scale food manufacturing, and it is also expected that this technology could increase productivity and support the generation of new products with changes in texture, flavour and structure.

The results of the analysis of microfluidics feasibility for application in distributed manufacturing systems are included in Table 11. Due to the fact that distributed systems are expected to require smaller production volumes, it is apparent that microfluidics could fit RDM production needs. Moreover, the high resource efficiency of microfluidics processed products regarding materials and water, and its ability to preserve nutrients and sensory characteristics could support the successful utilisation of microfluidics in RDM. Furthermore, research has shown promising results regarding the potential for product customisation through examples of applications for nutrients encapsulation. On the other hand, current costs of operation and equipment, and limited availability of food-grade ingredients to process utilising this technology could delay wide scale adoption by food manufacturers.

Microfluidics limitations which currently make infeasible its utilisation in centralised manufacturing systems could represent opportunities in distributed production systems. Once the barriers of limited ingredients and the complex control of processing parameters are overcome, the application of microfluidics to RDM could exponentially generate opportunities for distributed manufacturing of numerous food products that more mature available food technologies cannot enable due to innate limitations.

Table 11. Microfluidics technology assessment in a distributed production system



Microfluidics Technology

Functionality: emulsification, encapsulation.

Novelty: energy usage reduction, potential nutrients encapsulation application.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◔	◔	◕	◑	◕	○	◑	●	◔	◕	◑	◔	◔	○

4.3. Physical processing technologies

Physical processing technologies range from preparation of ingredients for manufacturing up to materials handling and packaging of final products. The innovative physical technologies selected to be reviewed in this report have significant potential to play an important role in future food RDM.

4.3.1. Extrusion technology

Extrusion technology involves a mixing phase for the ingredients, and a cooking phase which is followed by shaping and forming steps. It is a high temperature, short time process which not only cooks, but also increases shelf life of food products by inactivating microorganisms and enzymes while reducing water activity. Extrusion outputs can vary depending on the processing temperature offering different results based on cold forming, low-pressure extrusion, and high-pressure extrusion. The selection of the most suitable extrusion technology depends on the nature of the ingredients that need to be processed, the density of the final product, expected production rate and the desired physical and sensory properties.

Table 12 summarises the results of the analysis of extrusion technology based on RDM assessment criteria. Extrusion has been implemented in numerous centralised food manufacturing systems (cereal and pasta) and offers processing flexibility, speed and maturity. These together with a high level of consumer acceptance of products manufactured using this technology and low operational costs would support the utilisation of extrusion in small scale distributed systems. In addition, compared to other heat processes, this type of processing technology offers good preservation in terms of nutritional value retention and sensory properties [5]. The process flexibility to produce multiple product types using different ingredients and raw materials could also be a key factor in implementation of RDM, enabling localised food production based on existing regional quality of primary ingredients.

Table 12. Extrusion technology assessment in distributed production systems

Extrusion Technology

Functionality: processing, preservation.

Novelty: ingredients upgrading, time reduction, flexible processing.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
●	◕	◕	◑	◑	◕	◑	◔	●	◑	◑	◑	◕	◕

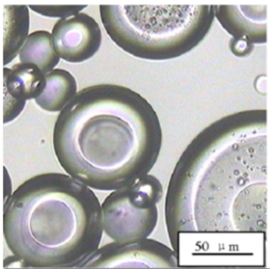
4.3.2. Membrane emulsification technology

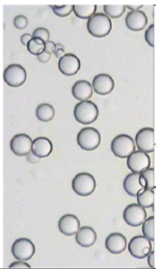
Membrane emulsification is a novel technology capable of directly producing individual droplets with the final desired size for food emulsions [12], which compared to traditional technologies that were based on iterations of breaking down processes, can be more efficient in terms of time, materials and energy. Moreover, the reduction of thermal and shear stresses offered by membrane emulsification can also provide higher quality products with better sensory characteristics.

Table 13 shows the suitability analysis of membrane emulsification technology in applications to RDM food systems. Membrane emulsification still faces some challenges in order to reach the maturity level required by large scale centralised manufacturing. Factors such as the membrane clogging and the control of droplet size still need to be further investigated to avoid products which do not comply fully with the specifications. The high quality of food products produced using this technology, the extended shelf life due to the low heat and shear rates, and the increased nutrient preservation compared to other emulsification technologies could support its utilisation in distributed manufacturing systems.

Membrane emulsification currently yields a low throughput capacity that may limit its potential application at large scale production. However, this technology could generate productive and profitable solutions in small scale RDM implementations. There are other food technologies such as robotics technology or nanotechnologies which, if applied in conjunction with membrane emulsification, could optimise the products to provide even better quality and support manufacturing operations to increase efficiency and productivity. Future development could lead to the widespread use of membrane emulsification in distributed food manufacturing based on product quality and minimal damage degradation of ingredients.

Table 13. Membrane emulsification technology assessment in distributed production systems





Membrane Emulsification Technology

Functionality: emulsions production.

Novelty: processing time reduction, improved emulsions generation.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◑	◔	◑	◔	◕	◕	◑	◕	◔	◑	◑	◑	○	○

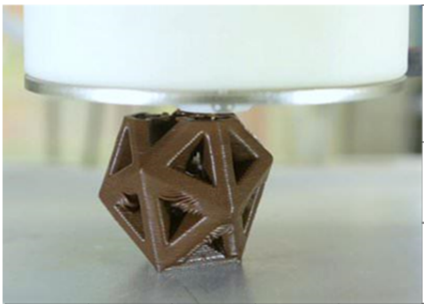
4.3.3. Additive Manufacturing technologies

Additive manufacturing, also known as 3D printing, is an emerging technology which is currently in the early stages of development for food applications. This technology is based on the concept of creating products by building their structures from different layers with the support of mechanical technologies that are capable of printing one layer at a time utilising different food grade materials [8]. The process of manufacturing food in an additive way has generated numerous opportunities in terms of product customisation, just in time production and production of complex products. This technology is still the subject of research into high yielding methods of generating products with complex food materials, and as a consequence, it is difficult to understand its potential and limitations.

Table 14 presents the results of the suitability analysis of additive manufacturing in future RDM applications. This assessment was carried out considering the current state of development of this technology and its potential future opportunities. If these expectations are met, it is envisaged that additive manufacturing will significantly benefit distributed production systems in multiple ways. This could range from high process flexibility using various ingredients and process re-configurability for new product formulation to substantial opportunities for customisation of food products and resource efficiency (zero waste).

It is clear that there are still numerous barriers in terms of unknown costs, consumer acceptance and limited throughput capacity, which need to be addressed before there can be successful applications of this technology. If future technological developments can successfully overcome these limitations, it is expected that future distributed food industry will utilise these technologies in most of their production facilities.

Table 14. Additive food manufacturing assessment in distributed production systems



Additive Manufacturing Technology

Functionality: production, product customisation, structure design, nutrients incorporation.

Novelty: new structures, optimised resource usage, new product development.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◔	◑	◕	●	◔	○	◑	◑	◔	◕	◕	○	◔	○

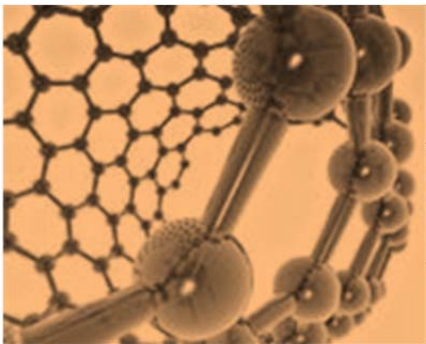
4.3.4. Nanotechnologies

Nanotechnology is the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the nanometre scale [41]. There are various types of materials that can be produced at nanoscale: one dimensional materials (very thin coatings), two dimensional materials (nanowires and nanotubes) or three dimensional materials (nanoparticles, such as very fine powder preparations). Nanotechnologies could help with structuring food products, adding nutritional value to existing products, assisting with shelf life and preservation operations as well as increasing consumer safety and packaging performance.

Table 15 shows the results of the RDM assessment considering the wider range of areas in which nanotechnologies are expected to provide potential benefits. For example, the ability to support product customisation by enabling reduction of fats and enhancing the absorption of vital nutrients could potentially support personalised diets based on individual needs. Furthermore, high levels of flexibility associated with nanotechnologies, both in terms of manufacturing operations and new product development, are considered to be vital enablers for future distributed food production and the ability to address local consumer needs.

It is also important to highlight that further research and innovation is required in order to overcome some of the key concerns that have arisen from nanotechnologies developments such as the operational risks and food safety. However, the promising results that the applications of nanotechnologies are showing together with the potential applications that are in development (e.g. packaging enhancers or new product formulations) point towards the conclusion that nanotechnologies could successfully be used in future RDM applications.

Table 15. Nanotechnologies assessment in distributed production systems



Nanotechnologies

Functionality: nutrients addition, product preservation, product enhancement, targeted nutrition.

Novelty: nutrients control, minimal impact in structures, packaging enhancement.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◔	◑	●	●	◕	◕	◕	◑	◔	◑	◔	○	◔	○

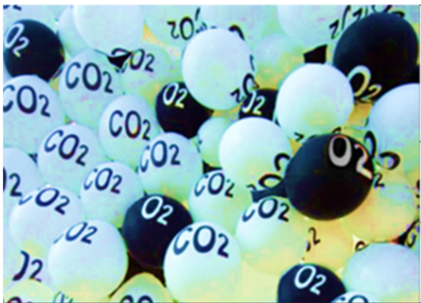
4.3.5. Modified Atmospheres technology

Modified atmospheres technology impacts the packaging stage of food manufacturing operations, and aims to enhance the shelf life of food products once they have been packaged and processed. This technology relies on the concept that the appropriate mix of gas and air inside the packaging could potentially preserve product quality for a longer period of time and therefore extend the shelf life [6]. Food manufacturers have always sought to discover new technologies capable of extending shelf life while granting similar quality to fresh products.

Table 16 shows the results of the analysis of the suitability of this technology in future distributed manufacturing systems. Modified atmospheres packaging is a flexible technology that can be applied to various products and is easy to integrate into other processing technologies. The high level of consumer acceptance together with increased capabilities for nutrients and sensory characteristics preservation of highly perishable products (e.g. meats or vegetables), while having minimum impact in production operations are all indicative of significant potential for inclusion of this technology in future RDM applications.

The initial capital cost for this technology, however, remains relatively high due to the specific technological requirements of being able to provide safe and secure extension of shelf life of food products. In addition, the specific nature of this technology limits its application only to solid foods which facilitate contact with the mixture of gasses and still safely guarantee microorganism control. The range of products which can currently be subjected to the shelf life enhancing capability of this technology include sliced fresh meat, bakery products, salads and other sliced fruits and vegetables; however, further research and development are underway to increase the range of products which can be supported by this technology.

Table 16. Modified atmospheres technology assessment in distributed production systems



Modified Atmospheres Technology

Functionality: product and nutrients preservation, shelf life extension.

Novelty: limited impact on product characteristics, improved traditional packaging preservation.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
◕	◕	◑	○	◕	◕	●	●	◑	◑	◑	◔	◑	◕

4.3.6. Robotics technologies

Robots are electro-mechanical objects which are controlled by programmes and have the capability of interacting with objects to conduct different physical tasks and actions as requested by the controller. They are one of the key components of automated manufacturing systems and offer the benefit of being adaptable and reconfigurable [3], which makes then suitable for processing different products with reductions in space requirements compared to other types of machinery. Robots can be utilised in all stages of food manufacturing due to their flexibility and adaptability.

Table 17 shows the results of the RDM assessment for robotics technology. The food industry is one of the last adopters of robotics technology due to steady increase in human labour cost. The high maturity level, integration potential with other technologies, consumer acceptance due to the repeatability and reliability of products, together with the very high processing speed make robots highly suitable for fulfilling many requirements of future distributed manufacturing facilities.

The widespread utilisation of this technology will rely on reductions in the capital cost together with the availability of skilled labour capable of handling such complex systems. In addition, recent extensive research and development has resolved numerous physical barriers (e.g. handling all kinds of food products in solid, liquid or gas phases) to its utilisation.

RDM systems are expected to demand flexible factories which can cope with highly variable customer demands, adapt to varying local market conditions, and be reconfigurable to allow introduction of new food products, all of which are indicative of the important role that robotic technology will play in future distributed food manufacturing.

Table 17. Robotics technology assessment in distributed production systems

Robotics Technology

Functionality: multi process management, materials handling, packaging.

Novelty: aseptic processing, errors reduction, perfect duplicability, risk processing enabler.

Maturity	Scalability	Flexibility	Customisation Potential	Nutrients & Sensory Impact	Shelf Life Impact	Integration Potential	Product Quality Impact	Throughput Capacity	Resource Efficiency	Safety	Capital Costs	Operational Costs	Consumer Acceptance
●	◑	◑	◕	◑	○	●	○	●	◑	◑	◔	◑	◕

4.4. Reflections on RDM assessment results

The assessment of the twelve food technologies in Section 4.3 has highlighted different affinity towards their application within RDM systems. Table 18 collates the results from these assessments to provide a comparative insight of their suitability for RDM. In addition, the highest scores and the second lowest scores for each technology are highlighted (Note: the lowest score may not be applicable to a criterion and therefore it has not been highlighted.). This aims to clarify the key enablers and barriers confronting food manufacturing businesses in the adoption of these technologies in future RDM applications.

Traditional large scale centralised food manufacturing businesses are facing new challenges due to ever-changing operational parameters such as rising fuel prices, increasing policy constraints towards the sustainability of their business, together with other concerns such as supply chain resilience and labour availability. The analysis in Table 18 shows that a number of these modern technologies (e.g. Additive Manufacturing, Microfluidics or Cold Plasma) could partially address some of these challenges and generate new benefits through a shift towards a distributed production of food products. However, in many cases it is also important to note that these technologies are often not complete production solutions, but one of the components within the overall process chain of production (e.g. Modified Atmospheres Packaging), or in other cases, simply enablers for other manufacturing operations (e.g. Robotics). Therefore, their ability to integrate with other existing traditional processes is a key consideration for their wide-scale adoption.

Finally, some of the modern technologies assessed in this report are still in the early stages of development within food manufacturing (e.g. Additive Manufacturing), and require further improvements to be used at an industrial scale. In this context, the assessment has often been carried out based on the limited available data and predicted future potential of such technologies. Nevertheless, to inform future research and development activities, an initial understanding of their capabilities and potential benefits is required to drive the food sector towards a more efficient and sustainable future.

Table 18. Summary of RDM assessment of selected technologies

Criteria / Technology	Maturity	Scalability	Flexibility	Customisation potential	Product quality impact	Product shelf life impact	Integration potential	Nutrients and sensory impact	Throughput capacity	Resource efficiency	Technology safety	Capital costs	Operational costs	Consumer acceptance
High Pressure Processing HPP	●	◑	◕	◑	◕	◔	◕	●	◑	◑	◑	○	◔	◑
Extrusion	●	◕	◕	◑	◑	◕	◑	◔	●	◑	◑	◑	◕	◕
Ultrasound	◑	◕	◕	○	●	◑	◕	◕	●	◑	◔	◕	○	●
Microwave	●	◕	◑	◔	◑	◕	◕	◕	●	◕	◑	◑	◕	◕
Innovative drying technologies	◕	◑	◑	◔	◕	●	◑	◕	◑	◕	◑	◔	◑	◑
Microfluidics	◔	◔	◕	◑	◕	○	◑	●	◔	◕	◑	◔	◔	○
Cold Plasma	◔	◑	◑	○	◑	◕	◕	◕	●	◕	◔	◔	◑	○
Membrane emulsification	◑	◔	◑	◔	◕	◕	◑	◕	◔	◑	◑	◑	○	○
Additive Manufacturing	◔	◑	◕	●	◔	○	◑	◑	◔	◕	◕	○	◔	○
Modified Atmospheres	◕	◕	◑	○	◕	◕	●	●	◑	◑	◑	◔	◑	◕
Nanotechnology	◔	◑	●	●	◕	◕	◕	◑	◔	◑	◔	○	◔	○
Robotics	●	◑	◑	◕	◑	○	●	○	●	◑	◑	◔	◑	◕

5. Research questions and challenges to support RDM

This report has focused on the role that food technologies could have on the wide scale implementation of RDM. Table 19 summarises the key research questions that have emerged in this study concerning future food technologies for distributed manufacturing systems.

Table 19. Research questions and associated potential food technology challenges

Research Questions	Potential technology challenges
Are existing food preparation and preservation technologies scalable and functional for future RDM food systems?	Adaptability, scalability, productivity, complexity, operability.
What other enabling technologies (e.g. intelligent control systems) influence food technologies for RDM food systems?	Integration, process control engineering, productivity optimisation.
Could novel food technologies be made productive and resource efficient for distributed manufacturing?	Sustainability, process design for resource efficiency, scalability.
Can novel distributed food technologies produce products with consistent quality?	Food process design, measurement tools and methods for food quality assurance.
What process flexibilities are required to produce customised and personalised food products?	Novel food ingredients, new preservation technologies, food packaging, product design.
What process flexibilities are required to deal with volatility in local market demands?	Scalability, modular process design, novel cleaning technologies, preservation, productivity.
How can we control the security and traceability of food products using novel food technologies?	Food security and traceability, intelligent food packaging.
Can novel food processing technologies become commercially viable in distributed systems?	Technology Readiness Level, public and private investment complexity.
Will additive manufacturing be a viable food production process for RDM to supply localised regions?	3D food manufacturing, novel ingredients requirements, productivity rates, limited product range.
What process features are required to make distrusted food products socially and societally acceptable (small factories in the middle of an urban area)?	Process noise and odour control, small scale waste water treatment, business social responsibilities.

5.1. Summary of research challenges in system, product and process innovation for RDM implementation

Specific research challenges emerge when considering the wide range of RID to support the RDM implementations at the three different levels that were identified in Section 3 of this report, namely process, product and system. Figure 8 depicts some these challenges, which are further explained below.

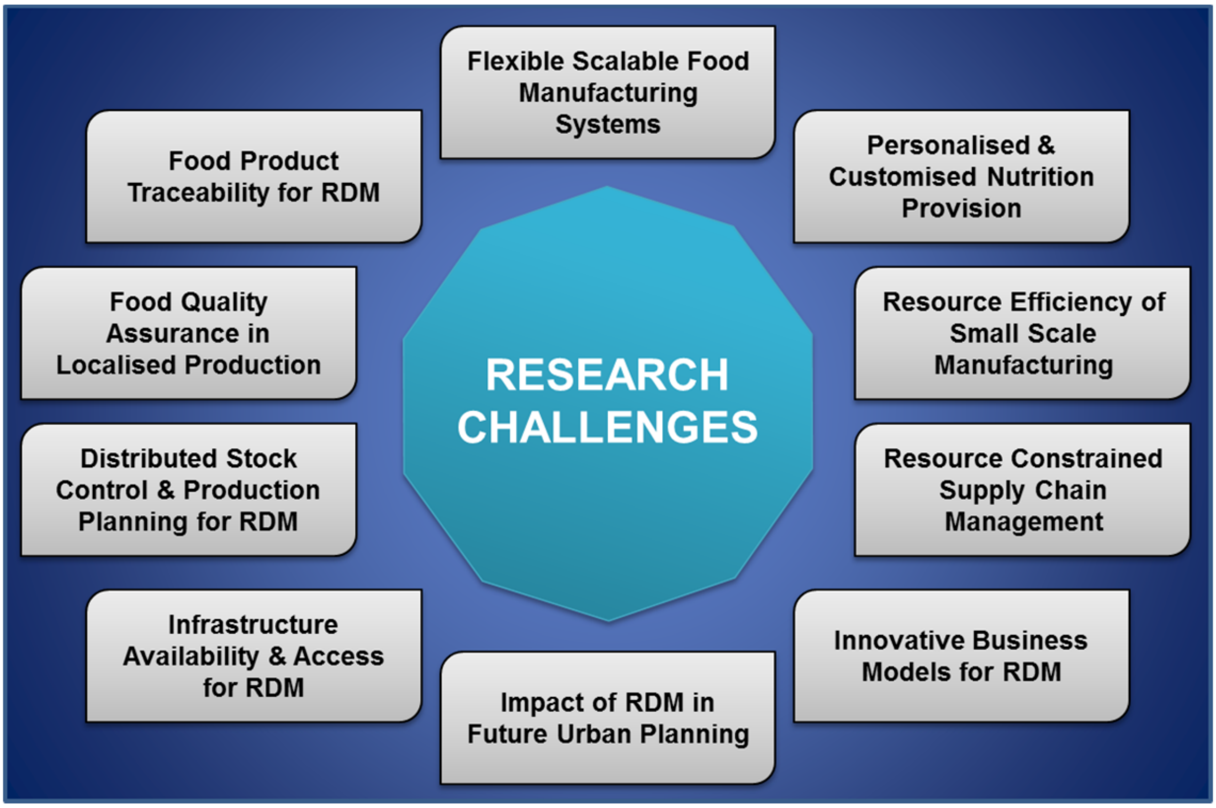


Figure 8. Research challenges for RDM

- **Flexible scalable food manufacturing systems**: this challenge is based on the idea of the development of manufacturing systems capable of adapting to changing products. A make-to-order philosophy of production could be followed which could have applications in small production runs while being profitable and sustainable.
- **Personalised and customised nutrition provision**: a predicted future challenge will be for food manufacturers to have the capability of producing customised food which can support personalised diets. It is expected to be a requirement of the future population and it could be enabled by innovative food technologies.

- **Resource (water, energy, materials) efficiency of small scale food processing**: centralised food manufacturing systems have been optimised to increase their efficiency in use of resources. RDM will face the challenge of not maintaining, but improving the resource usage in a distributed production system which is expected to have sustainability as a core component in its philosophy.
- **Food product traceability for distributed manufacturing systems**: the increase in production facilities and the complexity of value chains will challenge traceability technologies and their effectiveness when managing even more complex systems. RDM will generate new complex problems that will need to be addressed by future technologies.
- **Food quality assurance in localised production**: quality control will represent an important challenge with the increase in facilities and production lines. Moreover the changes in suppliers might lead to inconsistencies in product parameters. In addition, considering the potential customisation of products, the quality control standards might increase in complexity challenging the application by manufacturing businesses.
- **Distributed stock control and production planning for RDM**: managing production and stock control will be challenging for distributed food production systems. Numerous changes are expected to be required in traditional centralised theories and models to enable businesses to cope with a shift in demand management.
- **Resource constrained supply chain management**: in many situations distributed production will be constrained by the availability of resources. The most important challenge might be enabling future supply chains to operate in “local” impact areas, while keeping factories operational and providing consumers with the demanded products.
- **Infrastructure availability and access for RDM**: distribution of food production systems will also face the challenge of finding available infrastructure for changing production facilities and distribution routes to different areas in an efficient way. It is expected that in many cases investment will be required in order to succeed.
- **Innovative business models for RDM**: centralised business models will need to adapt to the distributed manufacturing philosophy. The challenge of generating new business models for the industry will be an important factor which will probably demand intensive work in order to productively support the shift in food manufacturing.
- **Impact of RDM in future urban planning**: traditional factory locations will need to change in distributed manufacturing. These changes might have an important role to play in the future urban planning of populated regions which expect to be supplied by distributed food manufacturing businesses.

6. Concluding remarks

Food manufacturing is one of the most important industries for both developed and developing countries. Traditional business models focusing on the centralisation and large scale production of food products are increasingly being challenged due to increasing demand for authentic local products, food waste associated with large supply chains, consumer demand for food sustainability, and concerns regarding the long-term resilience of complex food systems. Redistributed manufacturing is one of the new organisational structures that aims to generate a profound change in many industrial sectors, including the food sector, with significant potential for improved productivity and long-term sustainability.

This project focused on RDM for the food manufacturing sector and specifically in understanding how food technologies could enable the shift from centralised systems to distributed and localised systems. Numerous technologies are available or in development with promising potential for application in distributed food manufacturing. Fourteen criteria have been defined and used to demonstrate the suitability and applicability of these existing and emerging food technologies in support of RDM.

There are still key questions regarding the viability of RDM within the food sector, including the profitability of traditional technologies in smaller scale; scalability, reliability and ability of novel food technologies to produce high quality food products at affordable prices; and social and societal acceptance of small factories within urban areas. These concerns are indicative of challenges that need to be overcome through a set of carefully planned and managed research, innovation and development activities. One of the key complexities that may hinder the progress of such RID activities might be the lack of reliable environmental and economic data. For example, some of the novel promising food technologies are at different stages of development, and it is difficult to make reliable cost models and resource efficiency assessments, highlighting a need for further research.

It is also important to note that although food technologies are key enablers for wide scale adoption of RDM, broader product and system level considerations are required to successfully provide food businesses with the right information and tools to implement changes in the industry and drive food manufacturing to a more sustainable and efficient future. Considering the future of RDM, researchers across the globe are developing numerous materials, technologies and ideas, which are expected to overcome some of the shortcomings currently associated with distributed food manufacturing.

Finally, one of the main conclusions from this study is that increasing productivity, improving resilience and reducing waste are important considerations upon which the future of the UK food sector must be founded, and distributed manufacturing of our food products will play a vital role in the achievement of these goals.

7. References

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Appendix I: Innovative food technologies

Appendix I Table of contents

Appendix I List of Tables

A1. Microwaves

Microwave technology has some limitations and parameters (see Table A - 1). For example, when using this technology for heating, it must be taken into account that the process parameters can determine the capabilities of the technology regarding the heating of a specific product. Therefore, although it might be applicable to most products, its implementation needs to be balanced in order to provide the desired nutritional and sensory characteristics that consumers desire from a product.

Table A - 1. Microwave characteristics

Technology features	Key characteristics
Product parameters	- Food geometry - Package geometry and composition - Food composition and weight
Process parameters	- Frequency and power - Geometry and composition of the products - Dielectric constants, packaging materials and geometry
Limitations	- Cannot operate with highly conductive materials - Can have poor uniformity of treatment depending on geometry - Needs good containment to avoid leakage of microwaves - Requires water content for cooking applications
Other considerations	- Can be combined with other technologies - Very flexible applications in terms of products and processes

A2. Ultrasound

Table A - 2 provides a summary of the most important considerations for the application of ultrasound technology. These include some of the most important limitations that this technology has, such as the requirement for further processing to guarantee sterilisation, which can help when deciding the suitability of its application to specific products or processes. Furthermore, the key processing parameters, which are frequency, temperature, power and flow rate, need to be carefully balanced in order to be able to obtain successful outputs.

Table A - 2. Key characteristics of Ultrasound technology

Technology features	Key characteristics
Product parameters	- Application variants: direct, coupling or submergence
Process parameters	- Temperature, frequency, power, flow rate
Limitations	- Requires heat and pressure to kill spores and enzymes - Increased effectiveness only when combined with other preservation technologies - Physical depth of application - Possible effects on food structure and texture
Other considerations	- Can be used for food preparation or preservation - Good productivity and quality - Further development is required for certain applications - Complexity with scale

A3. High Pressure Processing

Although HPP has been subject to intensive research and development, it still has some limitations which need to be considered by food industries wanting to implement it in their processing lines (see Table A - 3). Factors such as constrained processing capacity and the need for further treatments in order to grant sterile conditions frequently impact the utilisation of HPP in food manufacturing. This technology can be used for the preservation of food products, offering better nutrient profiles compared to traditional food technologies.

Table A - 3. High Pressure Processing characteristics

Technology features	Key characteristics
Product parameters	- pH - Protein, lipid, salt or sugar content - Water activity
Process parameters	- Pressure, temperature and treatment time
Limitations	- High investment and maintenance costs - Processing capacity - Requires further treatments for sterilisation
Other considerations	- Requires adaptation to packaging specifications - Short processing but long set ups - Structural effects

A4. Cold Plasma

Cold plasma technology has several limitations and issues (see Table A - 4) due to its recent development for food manufacturing applications. For example, it must be noted that cold plasma technology is a superficial treatment. Therefore, products requiring more thorough sterilisation treatments cannot be processed using this technology or would require post processing to obtain a fully sterile product.

Table A - 4. Cold plasma characteristics

Technology features	Key characteristics
Product parameters	- Size - Geometry - Surface shape
Process parameters	- Gas mixture and pressure - Pulse voltage, duration and repetition rate - Distance between electrodes - Processing time
Limitations	- Superficial treatment - Potential damage to products under their surface - Oxidation of nutrients
Other considerations	- Suitable for continuous processing - Might require pre-treatment

A5. Innovative drying technologies

Spray drying

This technology is a complex method for fruit juice drying, but the benefits that it can offer in terms of stability and functional properties preservation have made it rather widespread. It offers short processing times derived from its single step process which can generate benefits for manufacturing operations together with good storage stability of the products.

Superheated steam drying

This technology can offer better energy performance and higher quality products compared to other drying technologies. It can also provide operational benefits by reducing processing times and increasing productivity since this technology can be simultaneously used as a sterilising, pasteurising or blanching technology. This technology has been successfully applied to a wide range of food products, but the limited availability of industrial equipment acts as a major constraint for future applications.

Freeze-drying

This technology offers numerous benefits such as higher stability of products at room temperature, better appearance and lower microbiological activity. Its products are easily rehydrated and make this technology highly competitive versus traditional dehydration technologies. Additionally, freeze-drying can offer good process throughput and energy savings.

A6. Microfluidics

Table A - 5 shows some of the most important identified characteristics that microfluidics technology presents regarding its potential food applications. Some limitations for its application such as the complexity of controlling the heat and mass transfer and the specialised equipment requirements need to be overcome in order to further explore applications across a wider range of food products. A potential future application is the encapsulation of bioactive compounds which could have a controlled mechanism of release in the human digestive system.

Table A - 5. Microfluidics characteristics

Technology features	Key characteristics
Product parameters	- Food grade ingredients - Structural requirements
Process parameters	- Heat and mass transfer control
Limitations	- High cost - Low flow rates - Specialised facilities
Other considerations	- Process intensification - Encapsulation

A7. Extrusion

Extrusion technology has a number of requirements and limitations in order to process certain products and ingredients which are shown in Table A - 6. Factors such as water content, recipe, and rotation speed need to be carefully analysed prior to utilising this technology. Extrusion flexibility makes it very useful not only for cooking various products, but also for the creation of new textures and the upgrading of secondary raw materials.

Table A - 6. Extrusion characteristics

Technology features	Key characteristics
Product parameters	- Water, protein and starch content - Extruder configuration - Recipe and physical limitations influence on shear rate
Process parameters	- Temperature and pressure - Rotation speed and dye profiles - Throughput and dwell time
Limitations	- Raw materials specifications - Adaptation of recipe, process and apparatus configuration - Need for trained employees and high capital costs - Potential destruction of vitamins, colours and flavours
Other considerations	- Sterilisation by high temperature - Starch gelatinisation and protein denaturalisation - Structure modification

A8. Membrane emulsification

Membrane emulsification still faces some challenges in order to reach the maturity level that industrial food production requires for its utilisation in manufacturing operations as shown in Table A - 7. Factors such as membrane clogging and control of droplet size still need to be further investigated to minimise losses in terms of materials and products which do not fully comply with specifications.

Table A - 7. Membrane emulsification characteristics

Technology features	Key characteristics
Product parameters	- Microstructure
Process parameters	- Membrane structures and materials - Process conditions for maximum throughput
Limitations	- Membrane clogging - Droplet size control - Throughput level
Other considerations	- Customisation capability - Energy saving

A9. Additive Manufacturing

Some of the most important considerations that additive manufacturing requires to enable food production are summarised in Table A - 8. Complexity of formulations, structural requirements of food products, and the variety of processing ingredients are some of the elements that need to be considered for the future additive manufacturing of food. Future development in additive manufacturing is expected to enable applications that will be more widespread across the food industry and to support personalised nutrition and product customisation.

Table A - 8. Additive manufacturing characteristics

Technology features	Key characteristics
Product parameters	- Printing process - Object geometry - Product formulation - Materials and recipes
Process parameters	- Food printing platforms - Printing recipes and technologies
Limitations	- Ingredients applicability - Cleaning complexity - Programming requirements - Mechanical force control
Other considerations	- On-demand production potential - Customisation of products - Personalised diets provision

A10. Nanotechnologies

Nanotechnologies will provide numerous benefits in the future across the whole food production system as shown in Table A - 9. Nanotechnologies could help with structuring future products, adding nutritional value to traditional products, assisting with preservation processes as well as increasing consumer safety and packaging performance. The immense potential that nanotechnologies have in the food manufacturing sector makes them an area with important needs for research due to the complexity of controlling and understanding nanoscale effects on food products.

Table A - 9. Nanotechnology characteristics

Technology features	Key characteristics
Product parameters	- Nanomaterials morphology and size - Chemical composition - Concentration and density
Process parameters	- Storage, processing and packaging
Limitations	- Further development for reduction of risks - Nano-metrology
Other considerations	- Safety issues - Potential future innovative applications due to recent development of the technology - Potential future diets improvement

A11. Modified Atmospheres

This technology aims to enhance food product shelf life once packaged and processed. Table A - 10 shows several considerations that need to be addressed correctly in order to safely apply modified atmospheres to packaged food products. Existing applications have shown good results and consumer acceptance and there are other applications in research and development which aim to increase the range of products which can be supported by this technology.

Table A - 10. Modified atmospheres characteristics

Technology features	Key characteristics
Product parameters	- Microorganisms activity - Product respiration
Process parameters	- Gas composition - Packaging materials
Limitations	- Only applicable to stable solid foods - Monitoring complexity - Potential unexpected microorganism growth
Other considerations	- Storage conditions - Air penetration into the package

A12. Robotics

Robotics has a number of limitations which could reduce the applicability of this enabling technology in food manufacturing operations as shown in Table A - 11. However, due to the extensive research and development that this technology has undergone, numerous physical barriers for its utilisation have been resolved and there are many solutions for utilising robots to process and handle multiple varieties of products in solid, liquid or gas phases.

Table A - 11. Robotics characteristics

Technology features	Key characteristics
Product parameters	- Quantity - Colour - Weight
Process parameters	- Autonomy level - Tool adaptability - Sensor types - Reprogramming potential
Limitations	- Gripper adaptability - Fixed working position - High capital investment - Complex adaptation to new processes
Other considerations	- High flexibility - Increase in productivity - Aseptic conditions potential