Preliminary project design for insect production: part 3 – sub-process types and reactors

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Abstract

This is a discussion about sub-processes suitable for the rearing of insect larvae on dry and semi-dry feeds. Three closely related, key aspects are dealt with as part of preliminary project design (PPD): the type of larval rearing sub-process to be employed, the reactor configuration and the operational approach to be used. A number of sub-process types and reactors are discussed. Because they are most commonly used in the industry today, all the sub-processes are ‘plug-flow’ (age stratified) and based on ‘passive’ reactors (contents moving through the reactor). Batch, semi-continuous as well as continuous sub-processes are dealt with and illustrated. Simulation to help the entrepreneur chose the most appropriate type of sub-process is highly recommended.

Keywords: batch; semi-continuous; continuous; reactor; larval rearing

1. Introduction

Once someone has decided to become seriously involved in mass producing insects and thereby qualifying as an ‘aspiring entrepreneur’, it is best for them to hold back and generate an overall plan of attack before investing too heavily in a specific concept or project. An outline of how one might proceed with this was presented by Kok (2021a, Figure 1). According to this scheme, one should start by negotiating several stages of early concept development supported by data acquisition while also gaining a minimum of practical experience through playing with some organisms and rearing methods. Although it may seem whimsical, ‘playing’ here is meant seriously, with the entrepreneur engaging in investigative, creative activity without having a limited, fixed objective. ‘Play is the highest form of research’ (Calaprice, 2010). At the end of these preliminaries there should, hopefully, be a fledgling concept that is suitable for further development through preliminary project design (PPD). During the PPD stage the project concept will be investigated experimentally as well as by means of modelling and simulation resulting, first of all, in a decision to proceed or not to proceed with that project. If the decision is favourable PPD work will also

result in decisions about the organism/feed combination on which the project will be based, the process type, the scale of operation, the system operating point and the control approach, etc. A method to estimate overall process mass and heat balances was presented in Part 1 of this series (Kok, 2021a) while process dynamics and how these depend on system kinetics and how they can be studied by means of modelling and simulation were discussed in Part 2 (Kok, 2021b). While, generally, the major features of the fledgling concept may survive, it is quite likely that during the activities described in Part 1 and 2 many of the other features will be substantially modified. This is normal and is to be expected. In fact, one of the main purposes of PPD is to locate a suitable operating point for the proposed system in a large possibility space and that may involve radical adjustments to the original concept. ‘Suitability’ of the operating point must always be judged according to a set of objective functions defined by the project developer, with one or more of those functions often being based on foreseen project profitability or return on investment (Kok, 2021b).

Although the author’s main approach is to deal with design and development situations in a formal, computer-based

Figure 1. Dynamics of a single tray, straight-batch sub-process.

manner it is also possible to do so in an entirely ‘informal’ manner. Thus, it is quite possible to analyse data and perform modelling and simulation *in situ* on human brains without having recourse to technological aids. In this way most of the PPD exercise might be carried out internally within the entrepreneur and even intuitively so that the entrepreneur them self may also not be actively aware of that occurring. A disadvantage of this latter approach is that it is difficult to work in a team in this way and that the results of the ‘computations’ are not easily justifiable. The formal approach, therefore, has major advantages for the development of larger projects.

In this paper a number of basic processes are discussed, mainly with application to the rearing of insect larvae on beds of dry or semi-dry material. Typically, any of the ‘mealworms’ (e.g. *Tenebrio molitor*) and the black soldier fly (BSF, *Hermetia illucens*) are reared under such conditions. Similar considerations apply to the rearing of other groups of insects such as crickets and cockroaches, but the methods and technologies discussed here are not directly applicable to them. In a complete insect-production process one would probably also deal with adult housing and egg production as well as egg and pupal incubation (for holometabolic insects) but only larval rearing is considered here. It seems most likely that, once the entotechnological sector develops sufficiently, the production of eggs will become a separate branch and will take place in a location different from where the larval rearing occurs. Accordingly, only larval rearing sub-processes are presented and discussed below.

Although they may be quite different in their operation and resulting dynamics, many of the rearing sub-processes are related in that the more complex ones are often multiplexes of simpler ones. A number of types of both simple and compound multiplexes are presented, collections and manifolds being the simplest types. Compound multiplexes may consist of collections of manifolds, etc. This terminology is explained in more detail below in the various sections on the sub-processes. More often than not, the simpler sub-processes will be the more suitable for smaller facilities and lower production volumes although a small-volume but fully continuous reactor and process are also described below.

2. The time-spaced, straight-batch, single-tray sub-process

In the most basic straight-batch arrangement eggs (or newly-hatched larvae) are added to a bed of substrate in a tray and simply left alone until they are ready to pupate. Depending on the species, it is often necessary to add some liquid water during the rearing period while, at the same time, water leaves the bed due to evaporation. The water vapor is then carried away as humidity in an air flow which can be due to either natural or forced convection. The air also supplies oxygen and removes metabolic carbon dioxide (as well as other gaseous emissions, e.g. from various *Tribolium* species (Duehl *et al.*, 2011; Roth, 1943)). Although this arrangement is labelled here as ‘batch’ it is, in reality only ‘quasi-batch’ because water, carbon dioxide and oxygen are exchanged continuously. It is correct, however, that the larvae are reared ‘batchwise’ in that they remain in

the tray for the entire rearing period. The heat and mass transfer balances for this situation were dealt with in some detail in Part 1 of this set of papers (Kok, 2021a) and a fairly rudimentary spreadsheet-based calculator was presented (as electronic supplementary material) with which such balances can be calculated. That type of method can be useful to explore the possibility space in a rudimentary way to find a suitable process operating point. Minimally, it provides guidance for further study on the process dynamics through modelling and simulation because it yields some basic data on mass and energy flows as well as yields, thus also providing some insight into cost effectiveness. The dynamics of a very basic straight-batch process based on a single tray being filled and emptied repeatedly are illustrated in Figure 1. Note that the output from sequential trays may be slightly different due to variations in eggs, egg age, environmental circumstances, etc. This process will be used only by a very small operation or for experimental purposes.

Evidently, in the straight-batch arrangement sufficient substrate must be added at the beginning of the rearing period to last until the larvae have grown to their harvest stage (which is often, but not automatically coincident with pre-pupation). One advantages of this is the simplicity of the setup and ease of system operation. One major disadvantage, however, is that bacteria will be able to grow throughout all the feed for the entire rearing period and can therefore consume a substantial fraction of the substrate while also giving off heat and emitting carbon dioxide. This will lower the yield of larvae ($\text{g_dry_weight_larvae_obtained} / \text{g_dry_weight_substrate_disappeared}$) and increase the service requirements of the process. Also, productivity ($\text{g_dry_weight_larvae_obtained} / \text{unit_time} \times \text{unit_reactor_volume}$) tends to be quite low in the straight-batch arrangement because, for much of the organism's residence time in the bed, the population density ($\text{g_dry_weight_larvae} / \text{unit_reactor_volume}$) will be fairly low. Of course, due to practical considerations, one can rear only a limited number of organisms in one tray. The tray itself can only be so large (actual limits are difficult to define, but there are limits) and the bed can only be so deep because oxygen needs to penetrate from the surface throughout its volume.

Consideration of the basic straight-batch system is useful mostly because many of the other larval rearing sub-processes are various kinds of multiplexes of this basic one. This means that most of the methods and reasoning developed for the basic straight-batch system apply equally to the more complex systems. Hence, the mass and energy/heat balances for these more sophisticated types of sub-processes, as well as the relationships between organism kinetics and process dynamics, are often closely related to those of the straight-batch type. Consequently, their balances and dynamics can usually be derived with similar methods and reasoning (and models and simulations) as long as the multifariousness introduced by collectivity and

manifoldness are taken into account. This is, however, not always true for some of the continuous systems in which the populations are mixed-age.

3. The time-spaced, straight-batch, collection-based sub-process

Once a practical size limit is reached for a single tray, the most obvious way to increase production is to operate the sub-process with a simple multiplex that is a collection of trays which are used in parallel and kept synchronised. They can be arranged side-by-side on a bench (not unusual for very small operations) or as a stack in a frame mounted on wheels (not unusual for slightly larger ones). The latter facilitates loading and unloading of the trays and also makes it easy to move them into and out of a controlled environment space (Kok, 2017). The facility is then usually operated to deal with a time-spaced sequence of collections with pauses in between for harvesting and processing the larvae, cleaning, feed preparation, administrative tasks, etc. The dynamics of this sub-process type are illustrated in Figure 2. In this case, there are 20 trays per collection, with some variation amongst trays shown with dotted lines in the production graphs. This could be due to any of the causes that can lead to widening of the distributions discussed by Kok (2021b). Although productivity of this type of scheme is relatively low, the simplicity of the physical arrangement as well as the ease with which it can be operated are very appealing for the small producer because all the activities are sequential. Thus, this type of sub-process can be operated by one person, even working on a part-time basis. All the product is available at the same time and can be separated, extracted, dried, etc. in a single work session. After that there is no immediate pressure to re-start the next collection; the pause between collections can be extended as needed so that tray preparation and inoculation can be timed for the convenience of the operator and the timing of the harvest can be planned for when labour will be available, e.g. during the weekend. Throughout the rearing period minimal effort is required; daily observation and watering are often sufficient.

4. The manifolded, straight-batch, collection-based sub-process

This kind of system is a compound multiplex in which collections of trays are manifolded, i.e. they are not sequentially spaced out in time as shown in Figure 2 but, rather, overlap in their residence time inside the reactor as illustrated in Figure 3. Generally, production will be higher and this arrangement is therefore more suitable for slightly larger-scale plants. If the collections are trays on rolling frames (Kok, 2017) one convenient arrangement is to move them sequentially through a tunnel reactor in which the environment is controlled. This type of reactor (which itself is static) is fairly easy and cheap to build and

Figure 2. Dynamics of the time-spaced, straight-batch, collection-based sub-process.

operate, with air flow coming in through a plenum from one side and out through another plenum on the other side. One advantage of this arrangement is that there can be different 'zones' along the length of the tunnel so that, if desired, the organisms can be subject to varying conditions during the rearing. The length of the tunnel will depend on the residence time of the frames and the desired output frequency. For example, if the trays need to stay in the reactor for 14 days and the desired output frequency is one collection per day, then the tunnel will have to accommodate 14 frames at a time. If each frame is 70 cm in depth, the tunnel will need to be about 10 m long, with a space allowance at both the entrance and the exit for loading and unloading. To attain a higher output frequency the tunnel can simply be made longer and the speed of the frames through the reactor increased. Evidently, this arrangement requires labour input more often than the simpler collection-based multiplex described above but, if the timing is set up properly, this system can still be operated on a part-time basis by one person who would need to process a collection and prepare a new frame of trays, e.g. every morning or evening.¹ One advantage of the manifold-based multiplex is that the equipment with which the larvae are processed (e.g. grinder, microwave dryer, separation unit, etc.) is used more often and is, therefore, easier to justify financially. This advantage becomes more significant as the production volume is increased.

¹ Thus, not unlike having dairy cattle that require daily milking, feeding, etc.

Once a maximum practical limit for the size of a single reactor is reached, to augment production further one can increase the number of reactors. If the system is based on a tunnel-type reactor a convenient arrangement is to put the tunnels side-by-side with a service space in between. Such a multiplex of manifolded collection-based reactors employed in parallel would probably be operated as a manifold of manifolds, with the reactors as a whole being kept out-of-phase with one another so that the same machinery can be used at both the input and output ends to service all of them, the result again being better utilisation of that machinery. These considerations are dealt with in more detail in Part 4 of this set (Kok, 2021c), in the paper on facility considerations. Although it is evidently possible to expand such a system to a very large capacity while keeping both the physical arrangement as well as the operation of the process quite simple, for larger systems it will likely prove advantageous, albeit at a cost of increased operational complexity, to instead use one of the fed-batch (as opposed to 'straight-batch') methods described further below.

5. The manifolded, straight-batch, single-tray-based sub-process

In this type of multiplex it is not collections of trays that are manifolded but, rather, single trays or bins. Thus, in this case units are not prepared, inoculated and incubated in sets but, rather, as individual elements which will usually be spaced out evenly in phase (and time). For example, if one tray is prepared every 10 minutes and the required residence time in the reactor is 14 days, then there will continuously be 2,016 trays in the reactor, one emerging

Figure 3. Dynamics of a manifolded, straight-batch, collection-based sub-process.

every 10 minutes to match the one being put in. Obviously, this arrangement calls for a specific kind of reactor. In this approach (used for the production of yoghurt, for example, where the fermentation takes place in the retail-level container) all the units are more-or-less kept moving continuously through the reactor while sitting on a belt or hanging from a chain. The situation is illustrated in Figure 4.

One advantage here is that the reactor's footprint can be kept fairly small because the reactor can be quite tall. Whereas a tall reactor is not impossible for the other multiplex types discussed above, in this case the situation is particularly appropriate. Another advantage is that a simple manifold-based process is very suitable for automation at both the input and output ends so that less manual labour is required per tray than for the previous two approaches. As well, because only small quantities of materials need to be dealt with at any one time, relatively small-scale machinery can be employed for tray or bin preparation, product separation, grinding, drying, bagging, etc. That machinery will be used quite intensively and thus have a high utilisation factor. Monitoring of the process is relatively easy because the units will be moving past the sensors regularly and, similarly, taking corrective action such as spraying water onto a tray is also fairly straightforward. In Figure 4, the 2,016 trays (not all shown!) are spaced out along 9 vertical lines and 8 turns. Hence, there need to be about 210 trays per vertical line. If they are spaced at 10 cm vertically, it should be possible to fit the assembly inside a reactor of 25 m high, allowing for head room, etc.

Although automation has many advantages, there are also disadvantages. Thus, machinery of this type is continuously active and moving and cannot be left to operate by itself for extended periods as is possible with more passive equipment. This means that the process will need frequent attention and someone needs to be close by 24/7. Another disadvantage of this type of process and of reactors such as shown in Figure 4 is their vulnerability to disruptions. For instance, if there is an electrical power failure there are several thousand trays stuck in a 25 meter tall tower with no way to unload them in a hurry. For this type of system a sufficient air flow for cooling, oxygen supply and carbon dioxide removal also needs careful consideration. These aspects need to be taken into account during plant design and will be addressed in some detail in Part 4 of this set (Kok, 2021c), in the paper on facility considerations.

The process based on a simple manifold as illustrated in Figure 4 is most suitable for slightly larger operations; it requires more investment to build, it needs more labour to operate, and it normally has a larger capacity than the previously-mentioned processes. And once it is installed, the production capacity of the plant can be increased quite readily by adding more reactors in a side-by-side layout, with spacing in between to create a multiplex of reactors. Of course, this possibility should be taken into account when the basic plant layout is created for that to be readily achievable. In order to maximise equipment utilisation on the input and output ends one would probably operate such a multiplex of reactors as a manifold, i.e. out of phase with one another. For instance, for a set of two reactors of the kind described above being operated 180 degrees

Figure 4. A simple manifold-based, straight-batch sub-process.

out of phase, one tray or bin would need to be prepared every 5 minutes and one tray would exit the assembly every 5 minutes. With several more reactors in parallel in the multiplex and operated equally out of phase production would really become 'semi-continuous' and approach the performance of a continuous process based on a plug-flow type of reactor as discussed further below.

6. The manifolded, immobile, fed-batch, collection-based sub-process

In the various straight-batch processes dealt with above the eggs (or very young larvae) were added to the tray or bin in which they were to be reared, together with the entire amount of feed they would need to reach harvest time (often at pupation, but not necessarily). Within this definition of 'straight-batch' is included the allowance that there will be an air stream through or over the surface of the bed and that water can be added as determined by the control system. The air stream will deliver oxygen to the biological reaction while also removing heat, carbon dioxide and, perhaps, some other gaseous by-products. The water that is added may contain some micro-nutrients. Although these processes are relatively straightforward in their operation, they are problematic in several ways. One problem is that

all the feed is present during the entire rearing period while most of it is not consumed until fairly late during the rearing. Consequently, most of the feed is subject to degradation and bacterial attack for a considerable period before being consumed meaning that a certain fraction of it may go to waste through bacterial 'composting' which also results in extra heat and carbon dioxide production (Kok, 2021a). This is especially problematic if the larvae are raised in an environment whose water activity is relatively high as is, e.g. normally true for BSE. The second problem is that all the feed, while waiting to be consumed, takes up space in trays and bins so that this space is not productive much of the time. This results in low productivity for the reactor. The first problem can be addressed by using an 'immobile, fed-batch' sub-process while both problems are addressed simultaneously by using a 'mobile, fed-batch' approach. As is to be expected, the solution to one problem creates some new difficulties and that is also borne out in this instance. Both solutions are bought at the expense of increased process and equipment complexity.

In the immobile, fed-batch sub-process the larvae stay resident in the same tray or bin throughout the rearing period, but feed is added either regularly or as required. Hence, this may be implemented as a modification to any

of the three straight-batch approaches discussed above: the time-spaced collection, the manifolded collection and the semi-continuous manifolded single tray systems. For the time-spaced collection system the modification is quite elementary. Thus, the operator will normally inspect and water the trays individually one or twice a day anyways so that for the fed-batch approach they will simply add some feed if this is judged necessary (quite similar to, e.g. traditional silkworm culture). For the manifolded-collection system the situation becomes more complicated since there are many more trays to look after and these may reside on frames or other structures inside long, tunnel-shaped or tower-shaped reactors with plenums on their sides for air supply and removal. A reasonably simple method to deal with this is to divide the reactor (or its equivalent) into a number of sequential segments and feed the trays during their transition between them. This is illustrated in Figure 5 in which a tunnel reactor is divided into three segments, respectively housing seven, three and four frames each of which hold 20 trays. Each day one frame exits and one frame is added so that the larvae have a total residence time of 14 days in the reactor and receive extra feed on days 7 and 10. Therefore, the operator, on a daily basis, has to feed two sets of 20 trays each, prepare 20 new trays and separate, dry, extract, etc. the contents of 20 outcoming trays. The production capacity of such a system can easily be doubled or tripled as demand increases by adding tunnels in parallel. These would then probably be operated as a manifold, i.e. somewhat out of phase so as to spread the work load out over a longer period and increase machinery utilisation.

For the manifolded, single-tray system (Figure 4) the situation is, in principle, no more complicated than for the time-spaced collection or for the manifolded-collection processes. Feed needs to be added to each tray at certain times during its transition through the reactor. Since the manifolded, single-tray reactor is likely to be automated already this may, in fact, be easier to accomplish than for the manifolded-collection arrangement. It will probably be necessary to add more sensors, control equipment and error detection circuits together with mechanical or pneumatic components to achieve the desired feed addition.

7. The manifolded, mobile, fed-batch, collection-based sub-process

Whereas in the immobile fed-batch process the larvae will stay in the same bin or tray during their entire development period, in the mobile fed-batch approach this is not so. Thus, as the larvae grow from perhaps 20 µg to 70 mg (depending on species, strain, feed, etc.) they will be transferred one or more times to different containers while also being fed on a regular basis. Although conceptually it is very appealing to have the young larvae initially resident in small containers and then transfer them to larger containers as they grow, there are substantial materials handling advantages to using a single size container throughout the process. This is especially true for larger operations in which container handling and cleaning will probably be entirely automated. Overall, in a 'mobile' system the larvae, as they grow, are given more room either by being moved to a larger container or by being distributed among more containers. As before, there are advantages as well

Figure 5. A manifolded, immobile, fed-batch, collection-based sub-process.

as disadvantages to the mobile approach. The biggest advantage is that the very young larvae will now occupy much less space and therefore consume less resources so that the overall volumetric reactor productivity is increased and the amount of resources consumed per unit larval weight is decreased. With other words, in this way the larval weight per unit reactor volume can be maintained at a more uniform level throughout the rearing period than with the immobile approach. The main disadvantage is that, again, equipment and operational complexity are both increased meaning that, generally, the mobile approach is worthwhile only for larger operations with manifolded systems that are collection-based. An example of an operating sequence for this type of sub-process is shown in Figure 6. It starts with a small collection of 10 trays containing very young larvae which, after four days, are then multiplexed to a collection of collections (the trays remain in phase!) by transferring the larvae to five sets of 20 trays each. Three days later these are then multiplexed further by transferring the growing larvae again, now to a collection of 50 sets (collections) of 30 trays each so that the total larval residence time is 14 days and the larvae are transferred twice while they are fed five times during their residence. For the sake of operational

simplicity the same trays are used for all three stages of the sub-process, resulting in a total of 1,500 trays at the end. Obviously, for a real system the timing, etc. will depend on the species and the growth conditions.

In the above example only one initial collection (of 10 trays) of young larvae is considered. But normally a system of this type will be operated as a manifold with collections of young larvae and resultant sets of mature larvae respectively entering and leaving the system at regular intervals. For instance, one set of 10 trays could be added every day and a corresponding set of 1,500 trays removed from the system every day. Then, based on the numbers from Case 3 in the electronic supplementary material of Part 1 (Kok, 2021a), the daily output would be 2,445 kg (wet weight, 1.63 kg/tray) while every day 675 g of eggs will be needed to be added to the 10 starter trays (67.5 g/tray). Thus, in this system there will continuously be 14 manifolded populations of larvae present (mostly distributed in collections of collections!) on a total of 10,840 trays.

Because the organisms are at quite different points in their life cycles, it is likely that the three rearing stages of any

Figure 6. Procedure for a collection in a mobile fed-batch sub-process.

population will occur in different reactors. It is not, however, always practicable to keep the members of a manifold who are at the same stage separated (N.B. these collections of different populations are at the same rearing stage, but out-of-phase). For instance, for the case mentioned above in which a collection of trays containing eggs or young larvae is added to the system every day there will be four collections of 10 trays each at Stage 1 of rearing, 24 hours out-of-phase, and these might very well be housed in the same reactor. Similarly, there will be three Stage 2 groups of 100 trays each (each group being a collection of five members, each of which is a collection of 20 trays) which might also be combined in one reactor while for the seven Stage 3 groups (each of which consists of 50 collections of 30-member collections of trays) it may actually be easier to keep them separated. A problem with combining collections in the same reactor space is that it increases the risk of contamination and will augment the magnitude of any disease outbreak that may occur.

Evidently, a mobile fed-batch system as described above can be expanded to almost any production scale by multiplexing in various ways. Two principal approaches are: (1) to increase the collection sizes; and (2) to decrease the manifold period. Thus, one might start off with an initial collection of 20 trays of eggs or very young larvae instead of 10 and in this way double the system's capacity. The same could be achieved by adding a 10-tray collection every 12 hours instead of every 24 hours, etc. Once the system is increased in capacity there are also productivity advantages to dividing the rearing period into more stages. It stands to reason that once demand goes beyond reactor capacity extra equipment must be installed. To double production of the above scheme, for example, a second set of reactors could be installed with the overall system manifold period being reduced to 12 hours so that 3,000 trays would need to be handled at the output end every day (4,890 kg/day wet larvae). If unloading is to be done during two four-hour work periods daily, that would result in a requirement to handle one tray every 9.6 seconds, resulting in a wet larvae stream of 170 g/s at the output. These quantities correspond to a small production facility (1,500–2,000 tonnes/year of wet material), with the rate and pattern of production approaching that of a semi-continuously operating plant.

A system of the type described here will require a substantial and robust materials-handling system to deal effectively with the various streams of solids like feed, bed contents and organisms. Dealing with live organisms and ensuring their survival during handling can represent some special challenges in this regard, e.g. during the transfers between stages. This is especially so since this type of system will need to be automated to a large degree, i.e. all the mechanical manipulations of materials will be carried out by machinery rather than humans. As well, almost all process regulation activities will be carried out by the control

system, i.e. regulation of temperatures, humidities, carbon dioxide content, air flows, error detection, etc. Because the survival requirements of most living organisms are quite exacting, in any bio-production process the potential for disaster is much higher than for processes based on non-biological agents. Accordingly, the opportunities for catastrophic failure are many-pronged and ever-present. As well, it would seem, the will of fate is unbending and the involvement of a human operator 24/7 in some capacity in this type of process therefore unavoidable. It may be possible to reduce that requirement to some degree by the use of artificially intelligent (AI) systems for routine supervision of the process. A major benefit of involving AI in this way also is that it lends flexibility to the process operation. For instance, with machines that are not tied to a diurnal cycle in a supervisory role it is relatively easy to manipulate production by adjusting the manifold period. For instance, to decrease production slightly, the manifold period could be increased to 25 hours instead of 24, something that is much more difficult to achieve with a process that is under the direct supervision of humans who work in eight-hour shifts according to schedules. The same approach could be used to increase production by shortening the manifold period somewhat. Of course, such measures are subject to the capacity of the reactors and other equipment, but they do facilitate the direct matching of production to foreseen demand.

8. Semi-continuous sub-processes

There is not really a rigorous definition of 'semi-continuous' but the essential characteristics of a semi-continuous process are that its output occurs quite frequently and regularly, in discrete packets. The output patterns of the various sub-process types discussed above are shown together in Figure 7 together with that of a truly continuous sub-process operating at steady-state, during which small, irregular fluctuations do occur but which are corrected by the control system. From this it is evident that the manifolded, single-tray (straight-batch or fed-batch) and the mobile fed-batch sub-processes are likely the most suitable types to produce a semi-continuous output. Of course, any of the other sub-process types can also be made to produce semi-continuously by manifolding. But their advantages are then often compromised, e.g. suitability for small-scale operation by one person on a part-time basis. The main advantage of semi-continuous operation of a plant is that it tends to lead to high utilisation factors for machinery and facilities, as well as high productivity of labour. This also holds true to some extent for approximations to semi-continuous operation, e.g. when the entire system output occurs in regularly-spaced, discrete packets during one eight-hour daytime shift. Generally, though, it is appropriate only for larger-scale systems. Thus, if a small-scale producer merely wants to increase their capacity to a moderate degree it is usually easier to multiplex as a collection rather than

as a manifold, i.e. install a parallel stream that is in phase, or almost in phase, with the first one.

At the end of the section on the manifolded, mobile sub-process an arrangement was mentioned that was composed of a multiplex of two fed-batch streams with an overall system manifold period of 12 hours, resulting in two four-hour unload periods per day during which an output rate of 170 g/s of wet larvae is achieved. That would approximate semi-continuous operation with a total annual production rate of 1,500-2,000 tonnes/year of wet larval material. In order to achieve full-time semi-continuous operation four more streams could be added in parallel to that multiplex and the system manifold period reduced to four hours so that every four hours one of the six manifolded streams would be unloaded, resulting in an uninterrupted output stream. Total annual production will then be about 5,000 tonnes per year of wet larval material, a volume comparable to that of a medium-sized poultry farm (about 3 million birds per year).

Worldwide, total (live) production volumes for poultry and seafood are about 100 million tonnes and 150 million tonnes per year respectively, and farm sizes are increasing rapidly. To compete directly with these products or to position insect-based protein in the feed market it will likely be necessary to build production facilities with a much larger

capacity than 5,000 tonnes/year so as to achieve lower unit costs. One might, for example, aim for a world-scale facility that outputs 200 times the volume of what has been mentioned so far, about a million tonnes/year. To do that, several strategies can be followed. The first one is fairly straightforward: massively multiplex, both as collections and manifolds any of the sub-processes that have been mentioned. The second one is more challenging but also more promising: change to a different processing approach altogether by moving to truly continuous operation. The latter approach has been adopted by most large-scale industries because, although it usually requires major investment to design and develop a continuous process, the productivity per unit investment that can be attained will often yield a high rate of return. The type of output pattern that can be expected from a continuous process operating at steady state is shown as the last item in Figure 7.

9. Continuous sub-processes

In classical process engineering the two main types of reactors used for continuous operation are plug-flow and continuous stirred tank reactor (CSTR). For both these types, when a system is fully functioning and operating at steady state, there is an uninterrupted flow of material into the reactor and there is simultaneously an equivalent, uninterrupted flow out. The main difference between the

Figure 7. Output patterns of the various sub-process types.

two is that in a plug-flow reactor materials of different ages do not mix whereas in a CSTR reactor all materials are constantly mixed. This means that if one takes a sample of the reactor contents, for a plug-flow reactor the sample material will have a very narrow age distribution whereas for a CSTR reactor it will have a wide age distribution. In reality, these two types are the extremes of a spectrum with most actual systems having some characteristics of both. Although there are some interesting aspects to continuous insect production with processes based on CSTR-type reactors, only the plug-flow case will be dealt with here because it is a direct continuance of the semi-continuous approach mentioned earlier. Moreover, only 'passive' sub-processes will be discussed, i.e. those in which the bed of feed containing larvae, etc. moves through the reactor on some kind of static support. In an 'active' sub-process it is the bed that stays in place and it is the machinery tending to it that will be mobile. Passive reactors can be either of the plug-flow or CSTR type. It is to be noted that plug flow reactors are most commonly employed for processing fluids in a confined space such as a pipe. However, as is done here, the concept can equally well be applied to a complex blend of finely divided solids, as well as mixtures of such blends with a liquid, reacting in a less confined space, such as on a belt. The texture of such a mixture may fall anywhere between that of a fine powder and a slurry, i.e. between that of dry corn starch or whole wheat flour and chunky peanut butter or concrete.

Thus, in true plug flow material travels through the reactor while its components interact. However, for the case of larval rearing, as for the other sub-processes discussed above, some components may leave or be added during the material's transit through the reactor. This is true, for example, for oxygen, carbon dioxide, water and even feed. Although this does require a slight modification of the classical definition of 'plug-flow', it interferes in no way with the essential feature thereof that, for any given element, there is little or no forward/backward mixing with elements that are younger or older. The result of this is that the age distribution of any element remains largely unchanged during its transit through the system except, of course, for the materials that leave or are added during that transit. The use of a plug flow reactor for larval rearing therefore tends to contribute very little to the widening of the organism's development distribution (Kok, 2021b). To assure or promote a longitudinal flow pattern of the bed through the reactor plug flow configurations customarily consist of a well defined, spatially confined path of much greater length than its diameter or width. A natural example of this (and probably the original prototype), is the intestine. In contrast, the CSTR is more like a stomach with its contents of all different ages being intimately mixed.

Whereas in all the previously-mentioned processes the bed of feed containing the growing organisms was confined

on five sides by the bottom and walls of a tray or bin, in a continuous process based on a passive plug-flow reactor the bed is confined by walls on only three sides, namely, by the bottom and two sides of the bed support. The bed is then moved along the length of the support in one of the unconfined directions by some means, several of which are discussed below. A conceptual portrayal for passive, continuous production is illustrated in Figure 8, with both top and side views shown.

In this case the bed support consists of a single, flat, level surface that increases in width along the transition path and on which the bed slowly moves forward (at this point it is not significant how that would be accomplished). As it transits along the bed length, the bed gradually increases in both width and depth due to the addition of feed. Accordingly, the bed volume available per larva increases as the larvae develop and grow. One great advantage of continuous processes is that automatic control is a natural adjunct to such systems and, typically, a continuous system will be equipped with arrays of sensors to provide data to an automatic control system which then utilises actuators to implement various control actions such as feed addition, water spraying, ventilation, etc. In Figure 8 these are respectively denoted with F, W and the combination of O₂, CO₂, and H₂O. A carefully designed control system can handle most routine process operating tasks and in this way result in very low labour requirements for the productivity it can achieve. Nevertheless, as for larger fed-batch and semi-continuous systems, for a continuously operating reactor in which many tons of sensitive and fragile material are present at any one time, some kind of overall supervision will be required 24/7. At this point it may be possible to assign part of that responsibility to an AI but some human involvement will probably remain necessary until AI technology reaches a greater degree of maturity. In Figure 8 are also shown input and output traces for a continuous system operating at steady state, i.e. not subject to any major disturbance. Due to unavoidable fluctuations in many factors, for real processes such traces will almost always show some variation. Continuous production based on plug flow was also described in a general way by Kok (2017).

To meet the physical requirements of a passive plug flow process, a great many operating methods and reactor configurations are feasible (besides all the possibilities for active plug flow processes). Some of those were reviewed by Kok (1983) and only several other ones will be mentioned here. The bed support, rather than being constructed as a single unit taking up a lot of floor space as depicted in Figure 8, might consist of a set of stacked belts moving alternately in opposite directions from one another, with the bed material dropping from belt to belt. In such a setup the reactor would have a pyramid shape, with a narrow belt at the top receiving the initial mixture of feed and freshly emerged larvae. Each belt below that would then be

Figure 8. A conceptual portrayal of passive, plug-flow based continuous production.

somewhat wider than the previous one with the bed resting on it being somewhat thicker also, due to feed addition at each transfer. In this way more bed volume will gradually become available to the larvae as they grow and move along the transit path.

A mechanically simpler arrangement than widening successive belts in a stack, but having the same effect, is to keep them the same width but run them at successively higher speeds. This is fairly easy to achieve with digitally-controlled motors whose speed can be varied over a wide range so that this approach provides for control flexibility. It would also not be difficult to integrate it with an AI-driven control system. At the same time as increasing the speed, the thickness of the bed can be increased by adding feed at each transfer, thus providing more volume per larva as they progress through the reactor. The use of these two methods combined is illustrated in Figure 9 for a stack of seven belts. For the sake of clarity, water spraying onto the bed and the removal and addition of gases by means of ventilation are not included in this diagram. Three major directions are available in this setup for the ventilation gas flow: length-wise, along the bed; sideways, across the bed; and vertically, upward or downward through the bed. As discussed below, the latter also offers some interesting possibilities for moving the bed along its transit path.

Rather than rely on the bed being moved along its support by mechanical means, e.g. on transport belts or with the use of scrapers, etc., it is also possible to have it slide down a gentle slope. On a smooth-surfaced bed this may be difficult to achieve in an organised fashion since the flow behaviour of powders and slurries is rather difficult to manage. What is somewhat easier to manage is to have the bed flow down a rough-surfaced slope under the encouragement of vibration and/or incipient fluidisation. To use the latter technique the top surface of the bed support needs to be porous so that short blasts of air can be blown through it in an upward direction, partially lifting the bed and allowing it to behave somewhat in a fluid-like manner. When this is done at regular intervals and in sequence along the length of the support, the bed can be made to flow down the slope smoothly while, as shown in Figure 8, feed and water are added to respectively increase the bed volume and regulate the water activity. This is a mechanically less complicated arrangement than a set of moving belts while it is also easier to widen the bed support along the transit path so as to increase the bed volume per larva as they develop. However, although the pneumatic approach is mechanically simpler than a set of belts, it is also more limited in its applicability because the bed consistency must correspond closely to the method. Thus, it is probably more appropriate for dealing with a

Figure 9. A plug-flow continuous reactor with seven stacked belts.

bed of fairly dry solids, as used for mealworms, rather than a wetter slurry as often used for BSF.

A reactor whose operation is based on this pneumatic approach is illustrated in Figure 10. Its inner and outer containment walls are conical surfaces of different angles, connected by the bed support which spirals downward at a modest angle. The degree of incline of the support must, of course, be smaller than the angle at which the bed would slide down the slope unassisted. The support consists of two surfaces, the bottom one being solid and impermeable while the upper surface is porous, thus forming a plenum between them with the bed resting on top of the porous surface. The fluidisation air will pass through this plenum and whenever the pressure is increased it will flow at an increased rate through the porous surface, causing incipient fluidisation in the bed making it flow a certain distance down the slope.² This is done, section by section, in an

upward sequence so that there is a gradual, slow descent of the bed together with its growing contents down the spiral slope and, ultimately, out of the reactor.

The support is therefore a sloping spiral that is level in the radial direction at any one point along its transit path, with the spiral gradually increasing in width from the top to the bottom of the reactor. The initial mixture of feed and freshly-emerged larvae (or eggs) is fed in at the top of the reactor and then, as the bed progresses down the slope, feed is added through ports in the top cone so that the bed gradually increases in depth as well as width along the path. If necessary, water can also be sprayed onto the mixture through nozzles mounted in the top cone. As for the other types of reactors, oxygen needs to be supplied to the organisms and heat and exhaust gases must be removed. This is mostly accomplished by continuously blowing air countercurrently over top of the bed, through the head space between the bed surface and the bottom surface of the spiral above. This main air flow (quite separate from the fluidisation air) comes in at the bottom of the reactor but, because the cross-section of the head-space becomes smaller along the path in the upward direction most of

² A constant, small, upward flow will also need to be maintained to prevent particles from falling through the holes; this will also help to aerate the bed.

Figure 10. A conical, spiral-bed continuous reactor.

that air will be exhausted through ports in the top conical surface. This will ensure that the air velocity over the surface of the bed is kept well below the saltation velocity of the bed particles. The surface velocity should also be kept fairly low to prevent excessive bed drying and case hardening and this limits the amount of heat and exhaust gas that can be removed. In turn, that will limit the bed depth and the bed occupancy density. As discussed in Part 2 (Kok, 2021b) the possibility space for such an arrangement would have to be investigated by a combination of simulation and experimentation.

In order to convey an impression of the scaling of such equipment some dimensions are shown in Figure 10 (all in mm). In this case the two surfaces are circular cones of 52° and 60° respectively, cut off at a height of 1,600 mm (elliptical cones might have some advantages in terms of path length and equipment placement on a plant floor). As shown, the footprint at the bottom is 3,126 mm in diameter while the width of the bed at the bottom is 408 mm and the width of the annular space at the top is 82 mm. In this case the bed support is made to slope down at 5°, with the bed thickness increasing at 1°, giving a total bed length of 15 m and a bed surface of 4.2 m². If the initial bed thickness at the top is 4 mm it will be 30 mm at the bottom while the total bed volume will be 0.082 m³ or 82 l. This suggests that it may be possible to produce continuously on a relatively small scale with this method. As need increased, production could easily be ramped up by multiplexing such reactors.

Two fabrication methods of this type of reactor are foreseen. The first is a classical approach based on sheet metal work (galvanised, aluminium, stainless steel) in which the various pieces are cut from flat sheets and then rolled and bent, assembled, and fastened together. For the example above the angles, etc. were expressly chosen so that the spiral surfaces could be cut from single, flat sheets. This is illustrated in Figure 10 with the outline of the bed support shape. A more modern, and likely less costly, fabrication approach would be to 3D print most of the reactor as a single piece. Thus, the external and internal conical surfaces together with the air inlets and outlets, the support surfaces, the feed and exhaust ports, penetrations for water sprayers and monitoring equipment, etc. could all be printed at once. This would eliminate the necessity to cut the spiral support shape from a flat sheet and thus remove some of the constraints on this design. It would also greatly reduce the labour costs for fabrication and assembly while ensuring structural integrity of the unit. Assemblies of this type can be 3D printed in a wide variety of materials including various plastics and even metals.

10. Discussion and conclusions

From the above discussion it is evident that the arrangement of the larval rearing sub-process, its operational details and the configuration of the reactor that is central to its functioning are intimately related. Thus, although they represent different aspects, these three factors need to be considered simultaneously in a coordinated fashion during the PPD phase of a project.

In order to arrive at a preliminary decision about what sub-process type to base the project on, the aspiring entrepreneur will have to gauge what organism/feed combination is most interesting, what scale they want to start operating on, what potential for production expansion they want to take into consideration, what labour will be available, what operating schedule they want to follow, what other process features will be required, etc. All of the sub-processes presented above have advantages and disadvantages in terms of all of these as well as their implementation cost, simplicity of operation, volumetric productivity, energy efficiency, etc. In all cases it is a matter of finding a good match between the entrepreneur's project concept, what a sub-process has to offer in terms of its pros and cons, and the operating point for any sub-process of interest. To evaluate the various alternatives that appear to be feasible for the conditions imposed, a modelling and simulation approach is very flexible and quite appropriate as long as it is supported by empirical verification. One very beneficial aspect of this is that it also allows the entrepreneur to explore new methods and approaches that had not been thought about previously. Thus, as well as being a tool to evaluate existing options, simulation facilitates the exploration of a much larger possibility space and the discovery of new potentialities.

For all the sub-processes discussed above the reactors are more or less 'plug-flow', i.e. there is very little mixing of bed contents of different ages so that the beds containing the larvae are substantially stratified. As well, they are all 'passive', i.e. the bed in which the larvae are reared moves through the reactor. It is, however, also possible to rear insect larvae in reactors of the 'CSTR' type, i.e. in beds that are not age-stratified. And sub-processes can also be 'active' so that the bed remains in place and the reactor equipment is mobile. Consequently, larvae can also be reared in active

plug-flow systems and in CSTR-type systems that can be either active or passive. These alternatives will be discussed elsewhere.

Conflict of interest

The author declares no conflict of interest.

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