A Review of Mesophilic Anaerobic Digestion Technology and the Drivers for Process Changes

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INTRODUCTION

This paper overviews the progression of Mesophilic Anaerobic Digestion (MAD) as its process developments have responded to ever tightening external constraints on sewage sludge treatment, recycling and disposal. It is a classic story of New Drivers producing innovative responses .

Recent significant developments in 'Advanced Digestion', largely in response to tightening bacteriological and pathogen residuals, have now achieved a critical mass with some dominant approaches, alongside others which have more recently migrated from pilot to full scale. This critical mass stage vitally reflects achievement of resilience in plant and product quality.

Whilst this paper focuses the New Drivers and New Solutions, it is essential that the longstanding drivers are not prejudiced in satisfying the most recent and potentially more demanding particular constraints.

A short look back at MAD's previous developments underlines its collective benefits.

From the early realisation of Dibdin, in late Victorian times, that sewage sludge released methane (used in plant lighting), to the 1930's developments when it was understood that sensitive biological processes were proceeding to convert a proportion of volatile (odorous) gases to potentially useful methane.

The 1960's saw the beginnings of process development within MAD with some understanding of the need for mixing and heating, regular feeding etc. Whilst not necessarily fully effective in terms of process inputs, thirty days was the normal notional detention time and feed sludges were thin, typically 2% as a mixed feed. The key driver then was odour reduction, not any biological standards. Odour reduction was to enable once remote sewage works, now engulfed by urban sprawl, to continue to be acceptable neighbours to the new property owners and dwellers. Against this driver, the process continued to slowly develop with the then process contractors offering innovations to various process inputs such as. heating which attracted many varied approaches.

The late 1970's and early 1980's saw a step change in both the understanding of separate processing inputs and their holistic interactions. These focused on resolution of the major inadequacies in mixing, feeding and heating. The new driver was an E.U Directive on improving bacteriological and pathogenic quality of sludge to land. The author's then employers, Severn Trent Water Authority, being landlocked and with only one incinerator for the then heavily metalled sludges from the West Midlands, clearly had the need but also had the will to invest in fundamental full scale innovation[1,2,3,4].

Process modifications giving both improved resilience, 12 – 15 days detention coupled with improved feed solids, gave typically improved throughput of existing plant by some four to six fold to meet previously un accommodated increases in sludge makes. Apart from the very significant reduction in additional plant needs and the capital costs of new ones, the sludge quality and odour suppression benefits were also supported by improved net gas available for economic power generation

Now in, 2006, continuing to protect the most environmentally beneficial and cost effective route of land recycling, this requires yet higher levels of sludge disinfection via. further reduced bacteriological and pathogenic residuals.

In order to resiliently deliver this new challenge without compromising the earlier drivers and benefits, recent sustained performances show that pre MAD process stages (biological, thermal, etc,) followed by conventional MAD offers the way forward in satisfying this latest driver.

This focus has itself forced some better understanding of the internal 'flow stages' of the Digestion process. The 1930's and 1960's considered MAD as a two stage process; the 1970's/80's postulated a set of three concurrent stages with hydrolysis/solution as rate limiting alongside plug flow as a contributor to improved pathogen reduction[3].

Current understanding such as a four/five component process, see later, with specifically optimised pre-treatment employing plug flow and thermal stress to achieve the extremely high levels of 'Biological Kill' is now required.

The body of this paper overviews the current state of play in Advanced Anaerobic Digestion (AAD) and the benefits/trade offs between the various processes in seeking to retain all MAD's previous necessary benefits. Further details of this will be expanded in other papers at this Conference.

As ever, but especially with sewage sludge, there are challenges and opportunities to be addressed; including deeper theoretical understanding of the Biochemistry, Biology and Process Engineering to support further stages of tailored performance optimization of particular drivers whilst maintaining these wider benefits. Indeed, the Defra Draft Odour Regulations mooted two years ago will ensure the focus on all aspects of sewage works odour suppression increases, i.e. one of MAD's previous vital drivers of odour reduction will again return to high focus – especially as it remains the whole route aspects of sludge recycling which are so vital,.

CONTEXT

The background in which both the new and historical drivers apply comprises not only higher bacteriological qualities but also a significant increase in sludge production as higher effluent standards require extended treatments, all coupled with population growth. Sludge production (as disposed) in 1991/92 was 6,476,400 tds/a in the European Community with the UK contributing 1,107,000 tds/a. By 2005 this was expected to increase to 9.3m tds/a for the Community as a whole and to 1.5m tds/a for the UK. For the UK this represents a 36% increase.

Additionally, the nature of these sludges to be digested is also changing with significantly higher proportions of SAS and growing contributions of 'inorganic' sludges from P removal. These changes will continue to develop as the E.U. Water Framework Directive impacts yet further.

As mentioned earlier, further reduced odour levels and their impacts on **all** sewage works related activities are currently just below the radar, having been signaled in 2003 at extremely low thresholds and which would be particularly difficult/expensive to achieve these indicative levels.

Furthermore, given the huge value of, but strategic vulnerability of sludge to land recycling, irrespective of actual sludge qualities given the emotional aspects within public policy decision making, these reinforce the imperative that sludge route investments are also flexibly and securely contexted against route contraction.

Should land disposal become even more severely restricted or ever eliminated, however irrational that may appear on rational risk etc criteria, sludge drying becomes the only immediately available alternate option in the current anti-incineration climate. What then is the ongoing route value of MAD pre-treatment process in such a context?

Without wholesale works redesign to abate raw sludge odours, MAD remains essential. Further, given the significantly higher overall VM reductions from the A.A.D processes and the increasing economic value of net biogas and generated power, the AAD pre-treatments described later will fund their own ongoing use, even without the strategic route 'value' from higher bacteriological quality sludge and other wider global sustainability benefits such as greater methane conversion and consumption to reduce overall greenhouse gas impacts are also delivered.

This 'future-proofing' within the AAD process by recognizing these innate flexibilities is vitally important as the viability of investments and returns over extended periods becomes more focused. These same commercial pressures highlight the need for plant and output performance resilience – all investments in plants have to do "at least what it says on the box" to secure overall viability.

Sustainability of the processes of sludge and sewage treatments require as high a net energy balance as is possible. Previous work[1] reinforces the huge value (Opex and Capex) from maximizing sludge thickness for MAD. At the circa 8% solids levels sought but infrequently achieved, process loading is not a limiter and so deploying the best practices in consistent thickening as already achieved by certain companies becomes more vital Again this aspect is developed later by showing the improving energy position with thicker sludges.

PROCESS DRIVERS

The Bacteriological Sludge Product Standards in the Defra Draft Guidelines (yet to be formally implemented but the de facto compliance target point for England and Wales) provide two sludge quality (bacteriological) levels for different levels of use restrictions.

'Treated' attracts the greater use restrictions and in process terms invariably has required an additional process stage to MAD – typically post digestion batch storage for some given period.

'Enhanced' provides the least recycling restrictions but requires one of the AAD pre-treatment processes described later to deliver both performance and resilience.

Whilst not identical in parameters, level or compliance regime, the USEPA Part 503, 1993 Regulations classes A and B are comparable.

Mention has been made of whole route considerations being fundamentally necessary to retain 'whole community' support. Alongside odour suppression at the sewage works, operational care must be consistent; namely any input raw sludge transport and handling; treated sludge transport; stockpiling and the subsequent land spreading must operate without annoyance. Failure at any stage, such as in the case of limed sludge final disposal in the U.S. attracts wider risks for all (although problems have also been reported earlier in this recycling route elsewhere).

Other key 'Community' stakeholders are the farmers and retailers who support overall sludge recycling. Retaining their support requires sludge recycling to remain an invisible, silent sentinel activity by avoiding **any** cause of avoidable problem for any of the stakeholders groups alongside promoting the environmental benefits of this route.

The strategic benefits and thus overall route and economic flexibility afforded by successful AAD processes are; lower net solids for disposal, even lower odour product sludge (note: liquors are often overlooked with major adverse consequences) and greater biogas generation, all depending on chosen pre-treatment option and consistent feed solids level attained. These are the combined benefits which yield the 'future-proofing' via innate self-financing of the pre MAD process.

Economic benefits from the energy balance/biogeneration optimisation arise from both ROCS and Energy Offset Allowances.

Figure 1[5] shows typical overall energy balances (usable and otherwise) between various pre-treatments whilst Figure 2 on a comparable basis shows the improving relationship between increasing sludge solids levels for a biological pre-treatment up to 8% (note; the CAMBI process operates at a reactor input of 14% solids and 165°C).

Figure 1 Energy Balances of Various AAD Options

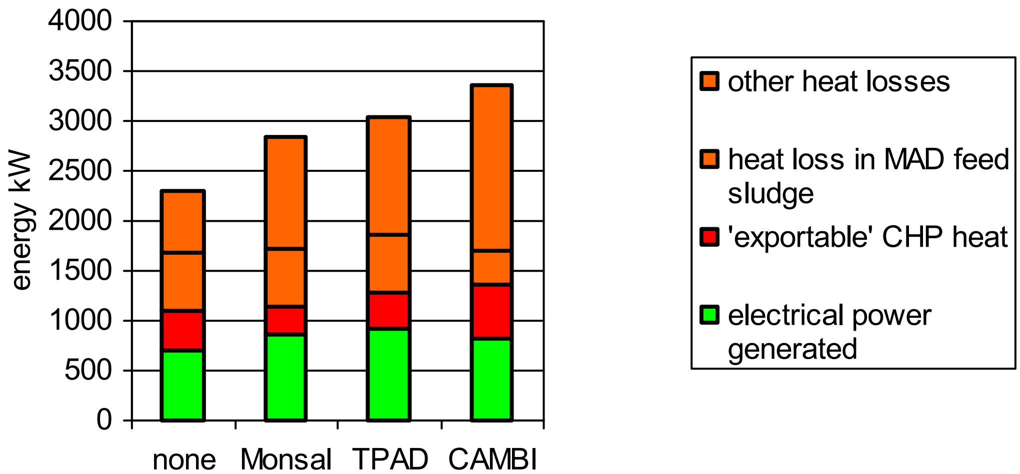
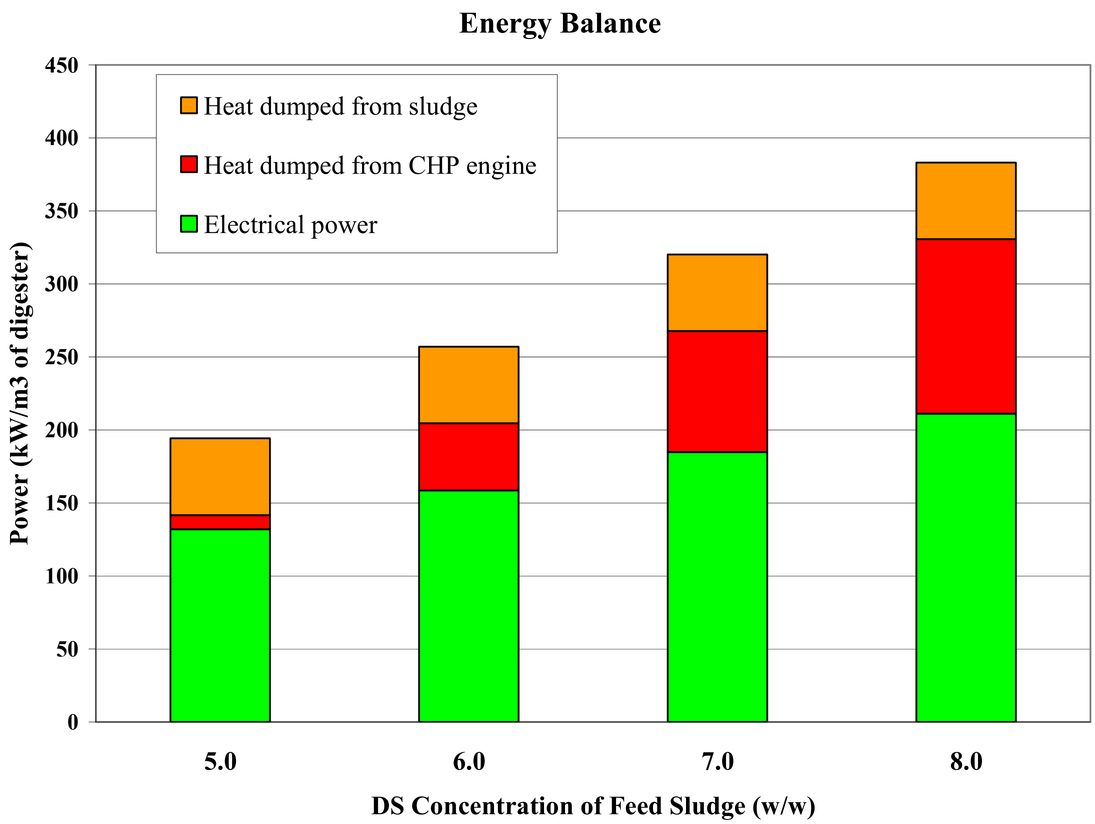


Figure 2 **Energy Balances for Biological Pre-treatments % volatile solids**



Figures 1 and 2 reinforce a very simple maxim borrowed from climate change drivers, "its about the carbon stupid". The often neglected maxim of sewage sludge treatments is, "its about the solids, stupid!" to which I would also add the often overlooked, but about to re-emerge, maxim, "its about reducing smells, stupid!" Let's sincerely hope none of us would neglect any of these maxims.

SOLUTIONS

Turning from the Drivers to the plant Solutions to meet the 'enhanced' (and treated) standards, they fall into essentially three basic approaches.

Biological with various reactor configurations (plug flow/batching); **Thermal** within a temperature/time matrix having been established as conservatively resilient and a variety of **Pasteurisation Hybrids** ranging from such as submerged combustion to aerobic "exothermic" pre-treatments. Many of the pasteurisation options, without or post MAD suffered failure through serious heating limitations and or sludge reinfection.

Looking at the individual processes, biological pre-treatments such as Enzymic Hydrolysis (EH) utilise sequential batch reactors with thermal options (42C and 55C) prior to MAD to exploit the benefits of the biological, thermal and plug flow components it embraces.

Themophilic processes (utilizing short detention such as TPAD 2-3 days) are also deployed as effective pre treatments. The historic problems of 'conventional' thermophilic anaerobic digestion re: a relatively narrow stable control window and odorous outputs appear to be overcome by a careful marriage to MAD.

A number of **purely** "**Thermal**" processes, from submerged combustion, to steam injection to CAMBI, a high temperature process operating at 133C – 200^{o}C and up to 12 bar pressure, in batch mode, treating 8 - 12 % feed sludges before entry to the MAD process.

Of the **Pasteurization Hybrids** (even chemical options such as perchloracetric acid, as well as of course the more widely deployed liming systems were tried) there was a huge conceptual flaw with normal post-pasteurisation, failing for the reinfection reasons indicated above. Of the pre-treatment variants many of the claims for greater sludge settleability etc., in processes such as Aerotherm (high intensity aerobic digestion) were never independently proven, nor indeed was their basic process efficacy to the author's knowledge.

Returning to the current 'critical mass', proven to meet the quality standards, biological options such as EH, EEH from Monsal or thermal from CAMBI and various alternatives such as that of Thames Water at Swindon, it is always useful to rigorously check each option offered in a comparable manner against a balanced score card such as:

- Are they effective?
- Are they resilient?
- Do they reduce odours **overall** and what, if any, are the odour risk areas from any aspects of process failure?
- Are their control windows suitably wide and stable for any anticipated feedstock (or other) variations?
- Are the liquors odorous, of high strength or low treatability (hard COD) or do they in any way prejudice the liquid effluent stream of the sewage works?

How do they interact with the MAD process in assisting the treatment duty required of that process i.e. how far do the various pretreatments go in overcoming rate limiting hydrolysis as well as contributing to acid formation through CO_2 production, or even providing some biogas production?

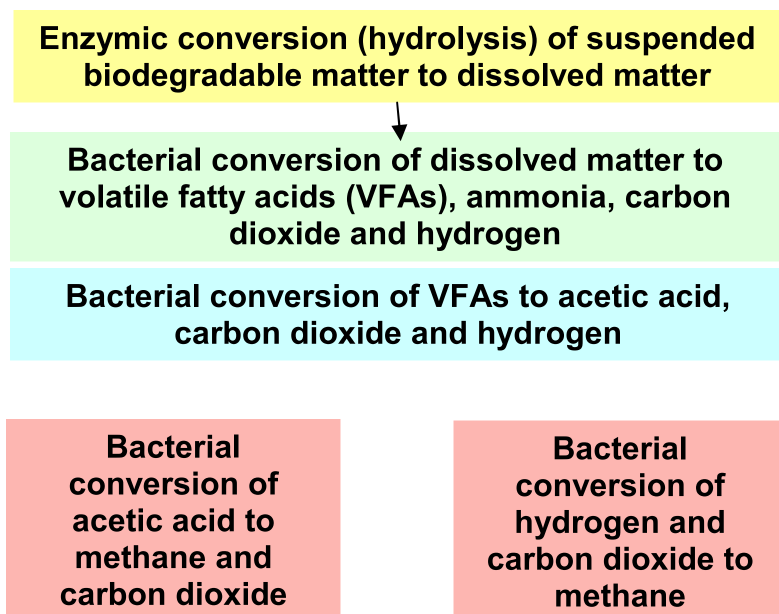
The order of benefit in assisting the subsequent MAD stages appears to be TPAD (thermophilic), EH/EHH ,and then the Thermal only processes (e.g. CAMBI)

AAD --- FURTHER CHALLENGES AND OPPORTUNITIES

Matching all the theoretical process aspects to the observed resilient full plant performance remains a challenge, one which is now worthy of greater focus to prepare to exploit the Digestion processes yet further. This effort can be focused for outright performance, resilience or economic (opex and capex) reasons.

A number of theoretical topics surrounding the basic chemistry, biochemistry and enzymic/bacteriological aspects of the key process options; along with such as subsequent settleability mechanisms, appear early priorities for good returns.

Fig. 3 Indicative Mechanisms of Anaerobic Digestion



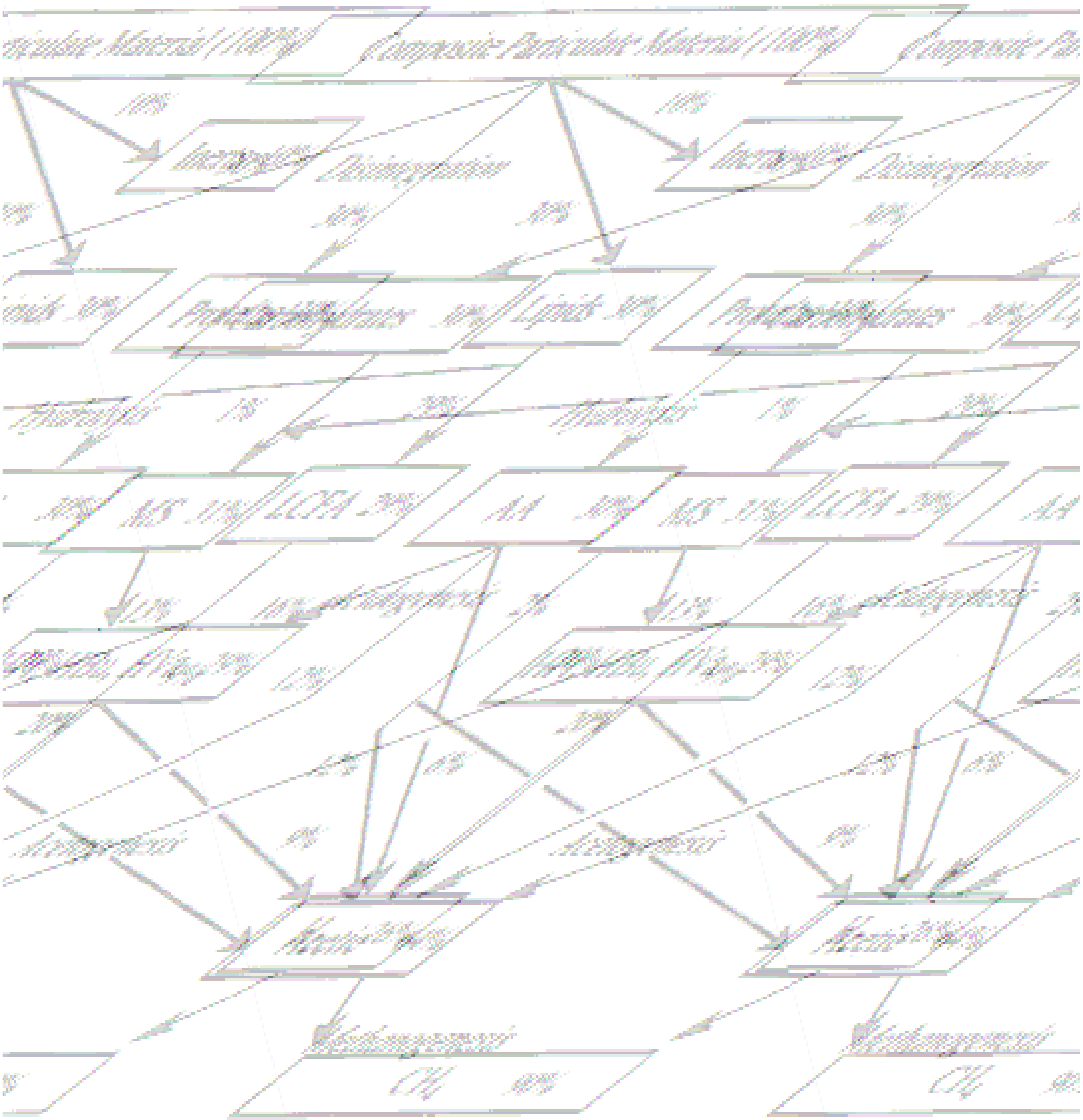


Fig. 4 Indicative Mechanisms of Anaerobic Digestion

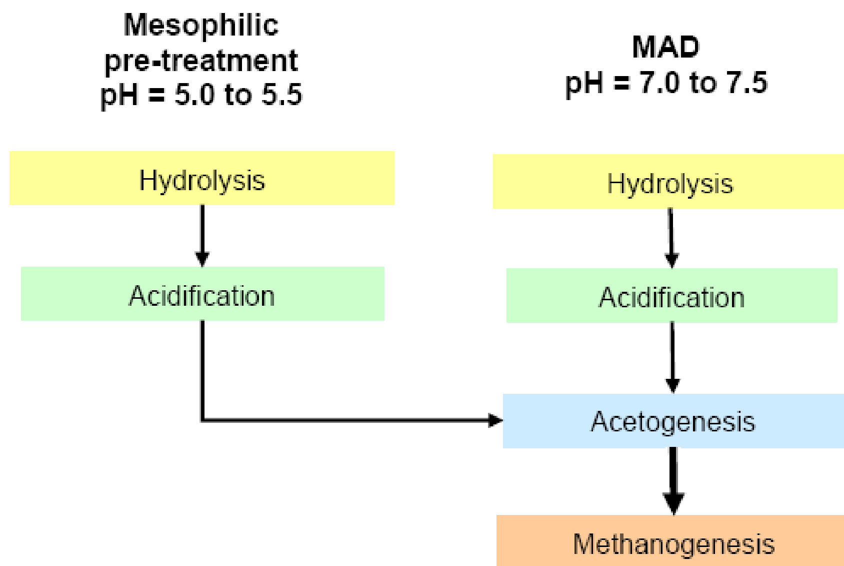


Fig. 5 Indicative Mechanisms of Anaerobic Digestion

Meanwhile such topics as that of Useful Net Energy Balance focuses the recurring operational challenge of delivering consistent higher sludge solids levels. The Author's personal view is that mechanically assisted dewatering (for transport and process optimization) allowing higher % solids to be blended 'down' will give greater resilience. The growing proportion of SAS in feeds makes this even more important. In all aspects of raw sludge thickening, transport, raw sludge stability and attention to avoidance of odour release are absolutely vital to facilitate the objective of whole route optimisation.

SOME WIDER AAD OPPORTUNITIES

Strong Industrial organic (typically food) wastes have long been a sensible feedstock for anaerobic treatments and this has generated a number of high rate processes. UK uptake is low due to high availability of the Trade Effluent option and 'fears of the unknown' for manufacturers in operating high rate biological systems. Despite such wastes often being fully solubilised/hydrolysed and often with elevated temperatures, the AAD processes still offer potential uprates in both overall performance and resilience.

A much closer application to that of AAD in sewage sludge is treating the putrescible (food wastes) component of municipal solid wastes (MSW). The hydrolysis benefits are comparable to those with sewage sludge, whilst the resultant enhanced net biogas production and odour suppression are also of high value. The high consequential value in the greatly enhanced recyclability of the remaining waste streams comes from treating the putrescibles components.

WHAT OF THE FUTURE?

Anaerobic digestion is the most widely used sludge treatment process worldwide, in the EU alone there are 36,000 digesters in operation, stabilizing around 3.5M dry tonnes yearly. This existing asset base is the result of decades of investment. AAD offers an opportunity to extend the value of these assets well into the future. The approach offers not only offer a lowest cost solution but also one that environmentally sound and sustainable.

MAD's and AAD's sound "thermodynamics" provide a glimpse into a future. One in which sludge processing contributes significantly not only via its longstanding key public health protection role but also with arguably the most difficult problem facing us all, namely global warming.

The attributes of such a future "dream technological solution" are likely to include;

- Sustainable biological (natural)
- High rate, intrinsically stable
- Odour free, sludge and liquors
- Lowest possible operating temperature
- High product quality (enhanced/Class A)
- Low tech construction and materials
- Maximum VM destruction and net energy

This list of process and product attributes may seem like a vision of heaven but ongoing work now in the UK is focused on such objectives with some closer to achievement than most would imagine, with much already achieved

SUMMARY

This overview paper has sought to context proven Advanced Anaerobic Digestion (AAD) options as continuing matches between Drivers and Solutions in which the Mesophilic Anaerobic Digestion (MAD) process has successfully delivered for over a century.

In the challenge of continuing to secure the strategically optimal route of sludge recycling to land, the MAD process has been again 'pushed' to deliver enhanced quality sludges to virtually undetectable levels of key bacteriological indicators.

Rigour in evaluating AAD options needs to ensure that all the accumulated and still needed benefits of MAD are retained, indeed the original odour reduction driver is soon likely to regain centre stage.

Further process developments ,whilst proven in full scale performance and resilience are getting ahead of areas of fundamental theoretical understanding in certain of the biochemical, enzymic and bacteriological pathways.

Being a self starting, natural, thermodynamically sound process (including many of the pre-treatment options), further optimisation and improved sustainability with increased net power export the investment from only a limited focused theoretical effort will ensure a further century of value to us all by optimally harnessing A.A.D.and its platform process of MAD.

ACKNOWLEDGEMENTS

The author most sincerely thanks colleagues at Monsal who have introduced him to the recent challenges of AAD and joined in interesting discussions about overall context and future developments. Very especial thanks are due to Dr Gary Hoyland who has kindly provided input from his recent I Chem E paper (ref, 5) and as ever supported robust, illuminating discussions ranging from plant details to theroretical process fundamentals. This overview reflects the personal experiences and views of the author.

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