Synergistic Effects Obtained by Combined Electron Beam and Microwave Irradiation

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Abstract. A new method based on microwave energy addition to accelerated electron beam energy for biological waste processing is described. The comparative effects obtained by applying separate and combined electron beam (EB) and microwave (MW) irradiation to the microbiological decontamination of the wheat flour, wheat bran and sewage sludge are presented. The research results demonstrated that the combined EB and MW irradiation produces the biggest reduction of microorganisms. The combined irradiation EB + MW decreases the wheat flour NTG by a factor of 7.38 and of 6.58 bigger than separate EB irradiation and separate MW irradiation, respectively. Also, EB + MW procedure decreases the wheat flour moulds by a factor of 3.7 and 2.43 bigger than separate EB irradiation and separate MW irradiation, respectively. The process has been demonstrated in a pilot-scale operation.

1. Introduction

Electron beam (EB) and microwave (MW) treatments are two of the most emerging biological decontamination techniques because in many cases provide distinct advantages over conventional processes in terms of product properties, process time saving, increased process yield and environmental compatibility.

EB irradiation is very effective for sterilization but required radiation dose is still high. Low irradiation doses are required for the process efficiency and a high dose rate must be used to give large production capacities.

The main idea of this work was to combine the advantages of both, EB irradiation and MW irradiation, i.e. high EB irradiation efficiency and high MW selectivity and volumetric heating for biological waste processing. In this work, the research regarding the investigations on the influence of separate and combined EB and MW irradiation on decontamination of wheat flour, wheat bran and sewage sludge are presented.

One of the expected and obtained result was the decrease of the required EB absorbed dose level by additional use of MW irradiation.

Thus, the ionizing radiation costs could be much reduced and the application of low intensity EB accelerators will become very economically attractive in the field of biological waste processing.

2. Methods

Both, EB and MW disinfection/sterilization processing are based on the radiation ability to alter biological properties of microorganisms especially due to the water presence in the living cells (both electron beam irradiation and microwave irradiation can much enhance the microorganism death rate).

A final comparative analysis of the application of EB irradiation and MW heating to the material decontamination processing has led to the following main conclusion: EB processes are very effective for material decontamination and the feature of inducing decontamination at room temperature brings unique advantages of EB over MW processing.

Regarding of food irradiation, at the prescribed dosage levels, irradiation produces small amounts of such compounds. However, fore more public acceptance, any dose level reduction in the ionizing radiation food processes is better.

The EB processing uses the Coulomb interaction of the accelerated electrons with atoms or molecules of irradiated matter. By this interaction ions, thermalized electrons, excited states and radicals are formed. The free radicals react with cell membranes, enzymes and nucleic acids to destroy microorganisms. The fact that the interaction by the radicals is effective to a wide range of micoorganisms is one of the advantages of the ionizing irradiation. The various products formed during radiolysis of water may, in this way, influence directly or indirectly the chemical processes and biological effects occurring in the individual compounds dissolved in water. The MW processing is a relatively new technology that provides new approaches to improve the decontamination process compared with classical methods. The frequency range of MW (300 MHz - 300 GHz) corresponds to quantum energies ($W=h\nu$, where h is Planck's constant and ν is the radiation frequency), which are small ($1.2\ \mu eV \leq W \leq 1.2\ meV$) as compared to that for ionizing radiation. Hence, MW cannot interact with atoms by generating transitions between principal energy levels, e.g. between a base state and an excited state. Instead of this, microwaves couple to transitions within the hyperfine structure of the dynamical state. Hyperfine splitting of the principal energy levels may be due to the interaction of magnetic moments of the electron shell and of the nucleus. The effect of MW is explained by their heating property on the polar or polarizable molecules of biological systems. Most reports suggest that for various microorganisms, the death rate is enhanced by MW heating more than by conventional heating and the more intense the microwave electric field, the more is the death rate enhancement. Also, due to the presence of water, which absorbs MW energy very strongly due its exceptional polarizability, it is possible to pump vibrational modes of DNA leading to unwinding and strand separation.

MW processes are less effective for food decontamination than EB processes but the cost of MW systems is considerably smaller than ionizing radiation systems. The research has shown that some microorganisms exhibit more sensibility to EB irradiation and other to MW exposure.

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Thus, by combined EB and MW irradiation could be possible to extend the kind range of microorganisms to be inactivated.

The main idea of this work is to combine the advantages of both, EB and MW, for the material microbiological decontamination, i.e. the EB high efficiency and MW high selectivity and volumetric heating, in order to assure higher material microbiological safety, to extend the kind range of microorganisms to be inactivated, to reduce the required EB absorbed dose level and irradiation time to a minimum and to decrease the decontamination process costs. Also, the combined effects of MW heating with EB irradiation could decrease the average microwave power level while keeping the temperature increase as low as possible.

3. Apparatus

For comparative studies of EB and MW irradiation an original installation which permits separate EB irradiation, separate MW irradiation and combined (successive or simultaneous) EB and MW irradiation was designed. Fig. 1 and Fig. 2 show schematic drawing and photograph of this installation, respectively.

This installation consists mainly of the following units:

- an EB source (ALID-7 electron linear accelerator of 5.5 MeV and 670 W, built in Romania, National Institute for Lasers, Plasma and Radiation Physics, Electron Accelerator Laboratory-Bucharest);
- two microwave injection systems of 2.45 GHz and 850 W maximum output power; a multimode rectangular cavity of 612 mm x 612 mm x 367 mm inner dimensions, in which are injected both EB and MW; a conveyor which moves the vessels with samples.

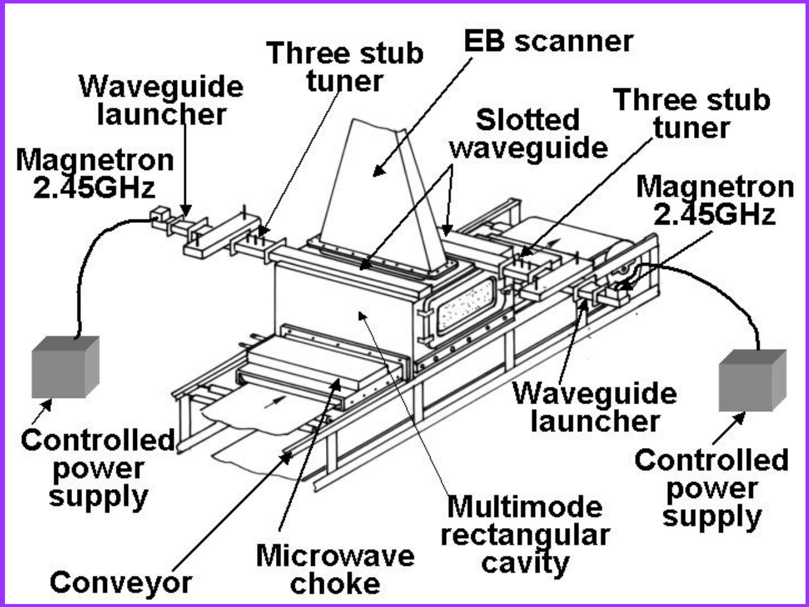

FIG. 1: Schematic drawing of the installation for combined EB and MW irradiation with conveyor

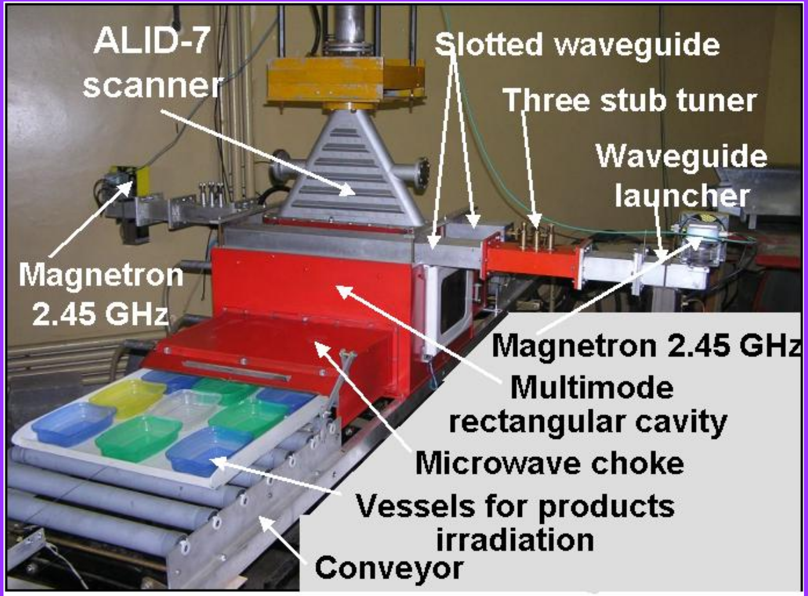

FIG. 2: Photograph of the installation for combined EB and MW irradiation

The following types of irradiation procedure were performed:

- **separate EB irradiation;**
- **separate MW irradiation;**
- **successive irradiation: first MW irradiation and then EB irradiation, (MW+EB);**
- **successive irradiation: first EB irradiation and then MW irradiation, (EB+MW);**
- **simultaneous irradiation with EB and MW, S(EB+MW).**

3. Results

The research comprised the investigations on the influence of separate and combined EB and MW irradiation of the following samples:

- sewage sludge of 10^{-4} m^3 (from a food industry wastewater treatment station - vegetable oil plant);
- wheat flour of 0.08 kg;
- wheat bran of 0.05 kg.

The samples were irradiated in plastic boxes (that are current used in MW ovens and which are EB resistant until 40 kGy) put in sealed plastic bags.

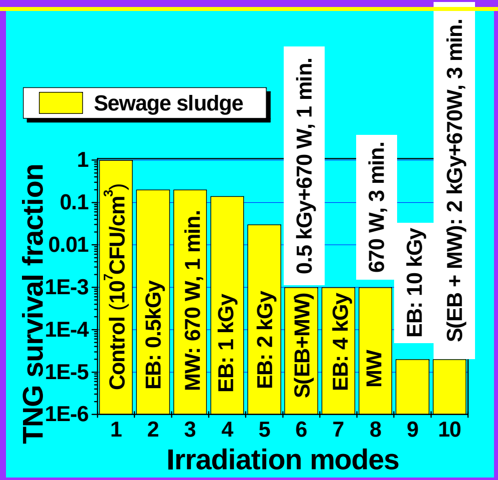

FIG. 3. The effect of different irradiation modes upon TNG

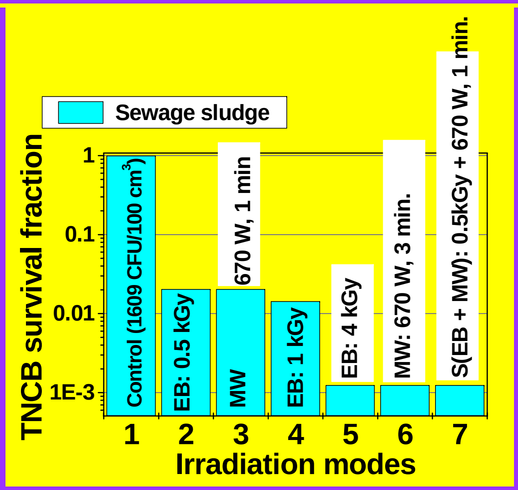

FIG. 4. The effect of different irradiation modes upon TNCB

The simultaneous EB and MW irradiation produces the biggest reduction of TNG and TNCB.

- 1-minute irradiation of simultaneous EB of 0.5 kGy and MW of 670 W has the same effect upon TNG (Fig. 3) and TNCB (Fig. 4) as separate EB irradiation of 4 kGy.
- 3 minutes irradiation time of simultaneous EB of 2 kGy and MW of 670 W has the same effect upon TNG as separate EB irradiation of 10 kGy (Fig. 3).

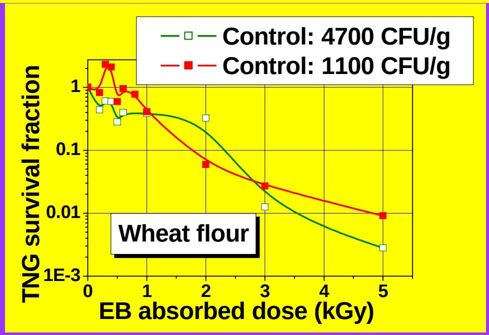

FIG. 5. The effect of separate electron beam irradiation upon TNG of wheat flour

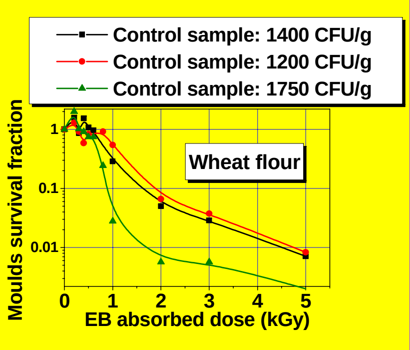

FIG. 6. The effect of separate electron beam irradiation upon moulds of wheat flour

Fig. 5 and Fig. 6 present the effect of separate electron beam irradiation upon TNG and moulds of wheat flour, respectively.

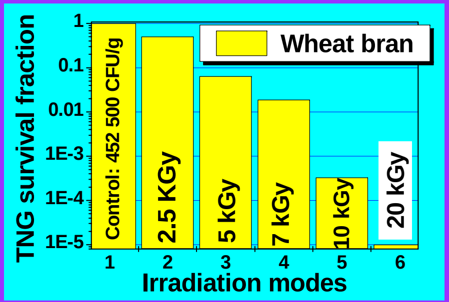

FIG. 7. The effect of EB absorbed dose upon wheat bran TNG

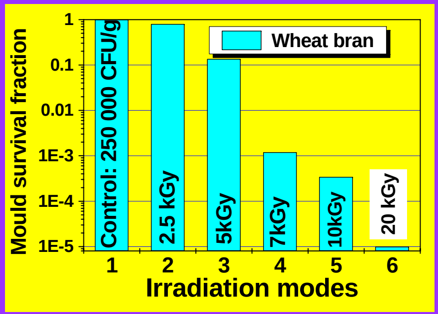

FIG. 8. The effect of EB absorbed dose upon wheat bran moulds

Fig. 7 and Fig. 8 present the effect of separate electron beam irradiation upon TNG and moulds of wheat bran, respectively.

All this figures show that, for separate EB irradiation, the survival fraction of TNG and moulds diminishes exponentially with EB absorbed dose.

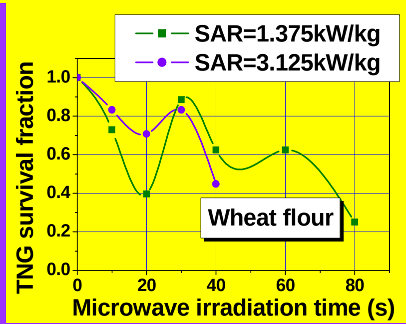

FIG. 9. The effect of separate microwave irradiation upon TNG of wheat flour

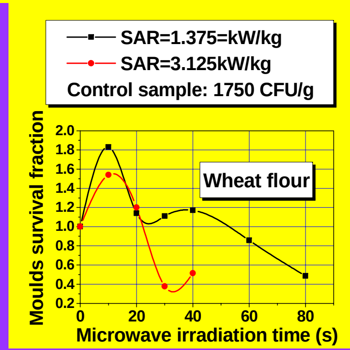

FIG. 10. The effect of separate microwave irradiation upon moulds of wheat flour

Fig. 9 and Fig. 10 present the effect of separate microwave irradiation time upon TNG and moulds of wheat flour, respectively.

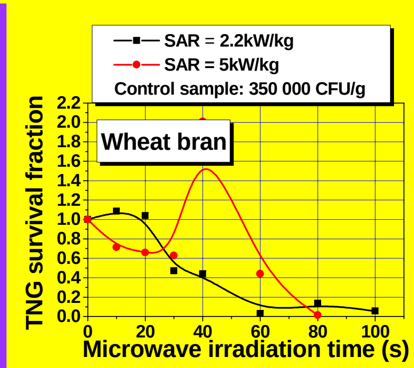

FIG. 11. The effect of MW irradiation time upon heat bran TNG

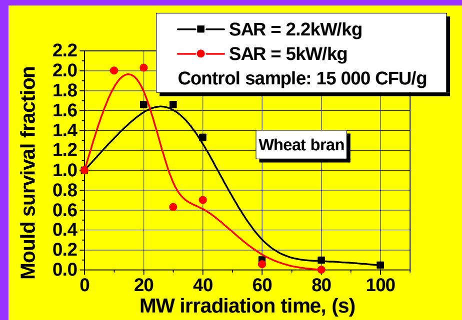

FIG. 12. The effect of MW irradiation time upon wheat bran moulds

Fig. 11 and Fig. 12 present the effect of separate microwave irradiation time upon TNG and moulds of wheat bran, respectively.

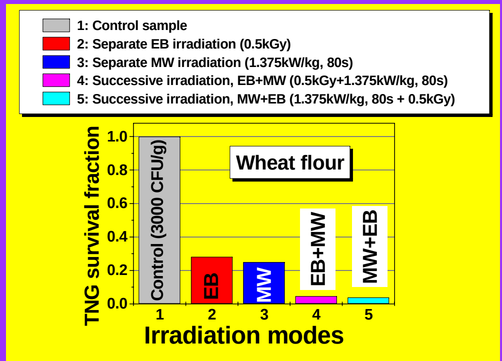

FIG. 13. The effect of different irradiation modes upon wheat flour TNG

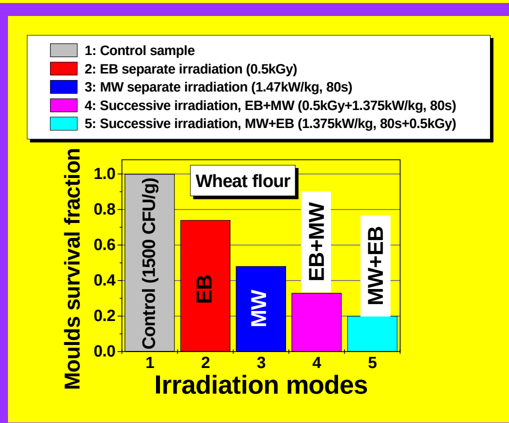

FIG. 14. The effect of different irradiation modes upon wheat flour moulds

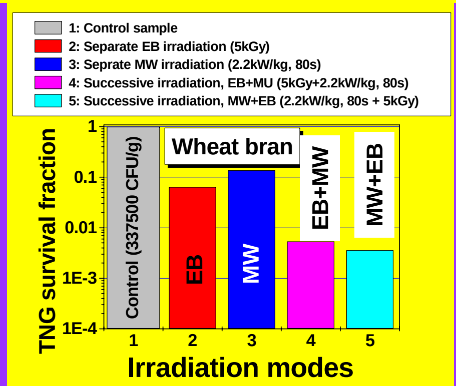

FIG. 15. The effect of different irradiation modes upon TNG of wheat bran

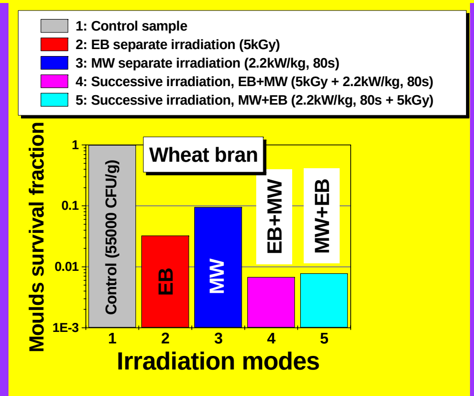

FIG. 16. The effect of different irradiation modes upon moulds of wheat bran

Figs. 13, 14 and Figs. 15, 16 give the comparative results concerning the effects of different irradiation modes upon TNG and moulds for samples of wheat flour and wheat bran, respectively.

The results regarding combined EB and MW irradiation, demonstrate that both irradiation procedures, cause greater lethal effects upon TNG and moulds than separate EB irradiation or separate MW irradiation.

As a summary of the above presented results, is demonstrated that:

- MW+EB irradiation procedure decreases TNG of wheat flour by a factor of 7.38 and 6.58 bigger than separate EB irradiation and separate MW irradiation, respectively;
- MW+EB procedure decreases the moulds of wheat flour by a factor of 3.7 and 2.43 bigger than separate EB irradiation and separate MW irradiation, respectively;
- MW+EB irradiation procedure decreases the TNG of wheat bran by a factor of 17.8 and 37.9 bigger than separate EB irradiation and separate MW irradiation, respectively.
- MW+EB procedure decreases the moulds of wheat bran by a factor of 4.2 and 12.2 bigger than separate EB irradiation and separate MW irradiation, respectively.

The EB required absorbed dose with MW+EB irradiation of wheat flour is decreased by a factor of 5 for TNG and by a factor of 2 for moulds compared to separate EB irradiation. The EB required absorbed dose with MW+EB irradiation of wheat bran is decreased by a factor of 2 for both, TNG and moulds, compared to separate EB irradiation.

4. Conclusions

Separate MW irradiation, as compared with EB irradiation that diminishes exponentially the viable cells versus EB absorbed dose, always induces an oscillatory decrease of survival fraction of microorganisms versus MW irradiation time: periods of germs inhibition or stimulation are followed by periods of germs stimulation or inhibitions.

Combined EB and MW irradiation produces the biggest reduction of microorganisms. In our opinion, it seems that microwave irradiation could cause the modification of the microorganisms sensitivity to EB irradiation. Thus, the application of combined EB and MW irradiation lead to greater lethal effects than the EB irradiation alone. Also, the tests demonstrated that irradiation time and the upper limit of EB required absorbed dose, which ensures a good decontamination effect, could be reduced by a factor at least of two by additional use of MW energy to EB energy.

Thus, The most important conclusion is that the combined electron beam and microwave irradiation could become a new disinfection/sterilization method, commercially viable alternative to classical thermal or chemical destruction.

Also, ionizing irradiation costs could be much decreased and the application of low intensity radiation sources, which are less expensive, will be extended for the sanitation/sterilization of a wide variety of materials including food items, medical objects, hospital waste, waste water and sewage sludge. The technology of sludge irradiation followed by composting could be developed to produce disinfected compost for agriculture.

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