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Effect of a static magnetic field on *Escherichia coli* adhesion and orientation

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Abstract

This preliminary study focused on the effect of exposure to 0.5 T static magnetic fields (MF) on *Escherichia coli* adhesion. We investigated the difference in bacterial adhesion on the surface of glass and of Indium Tin Oxide (ITO) coated glass when exposed to a perpendicular or to a parallel magnetic field to the adhesion surface (vectors of magnetic induction are perpendicular or parallel to the adhesion surface, respectively). Control cultures were simultaneously grown under identical conditions but without exposure to magnetic field. We observed a decrease in cell adhesion after exposure to the magnetic field. Orientation of bacteria cells was affected after exposure to a parallel magnetic field. On the other hand, no effect on the orientation of bacteria cells was observed after exposure to a perpendicular magnetic field.

Keywords: Static magnetic field; Cell adhesion and orientation; *Escherichia coli;* Fluorescence microscopy.

1. Introduction

The problem of bacteria attachment to abiotic surfaces has been investigated by many authors in order to well understand the physical and biological changes that can occur, in the bacteria-surface interface, when adhering. The main purpose of our study was to investigate the effects of a 0.5 T static magnetic field on a mutant *Escherichia coli* adhesion on two different abiotic surfaces. For this purpose, we used glass slides coated with thin semiconductor indium tin oxide (ITO) and a genetically modified hyper-adherent and fluorescent *E. coli* K-12 strain PHL969.

We used *Escherichia coli* because it is easy to manipulate. As an adhesion surface we chose a semiconductor surface: indium tin oxide-coated glass, in view of the fact that we planned to study the electrochemical kinetics of bacterial adhesion by the mean of the impedance spectroscopy and to ensure fast cover of surface with bacteria cells.

According to recommendations from the European Union (EU), static magnetic fields below 0.5 T are commonly considered quite safe for humans (Potenza et al. 2004) and no authorisation is required for installation and use of machinery with fields below 0.5 T. Therefore, we have taken this recommendation into account while choosing the applied magnetic field induction 0.5 T.

Since wild-type *E. coli* K-12 strains are not able to attach to surfaces (Vidal et al.1998), they were previously genetically modified in order to acquire the ability to colonize inert surfaces. This modification consists of an overproduction of curli, a particular class of pili resulted from a single point mutation obtained after the replacement of a leucine by an arginine residue at position 43 in the regulatory protein *OmpR*. The *ompR234* allele increases the expression of *csgA*, the curlin-encoding gene and the resulting overproduction of curli confers the adherence properties (Vidal et al.1998). These results showed that curli are morphological structures of major importance for cell adhesion to

inert surfaces and surface colonization and biofilm formation. This work also indicated that curli synthesis is under the control of the EnvZ-OmpR two-component regulatory system.

According to Marshall (1992), it seems that the first contact between bacteria and a surface implicates weak chemical bonds and therefore the bacteria can be removed from the surface after washing. This is called reversible adhesion. The efficiency of the "collision" between a bacterium and the surface depends on the culture conditions in the liquid phase (some parameters of the used broth can affect the envelope structure which can interact with that surface). It also depends on the substrate surface physicochemical state (Lejeune 2003). Particular structures of the bacterial envelop like fimbriae (i.e. curli) and adhesins have been described as essential for the reversible adhesion accomplishment (Vidal et al.1998).

Once the first stage of adhesion is established, the "surface sensing" process takes place and bacteria start to acquire information about the surface characteristics via their regulating and perceptive mechanisms. In the case of *E. coli*, curli synthesis is being reinforced and colanic acid exopolysaccharide secretion starts (Prigent-Combaret et al. 2000). This adhesion step represents the irreversible adhesion and colanic acid production is a fundamental parameter involved in this process. The end of the irreversible adhesion is characterized by the formation of a slimy layer on the colonized surface, called biofilm as a result of bacterial multiplication and production of extracellular polymers (Marshal et al.1971).

According to ZoBell (1943), immersion of a clean substratum in a natural fluid is immediately followed by fast and efficient adsorption of organic molecules to the surface, forming the so-called "conditioning film". Two types of bacterial interaction are then possible: weak chemical bonding between the bacterial envelope and the solid surface (or

the conditioning film) and bridging mediated by specialized bacterial structures of adhesion.

Increasing attention is being paid to the effect of magnetic field on the biological system and changes have been proved at different levels. Indeed, many studies have demonstrated an effect on the cell adherence, metabolism and genetic activity. Some investigations have been performed, under low magnetic field, using prokaryotic cells by studying their viability (Strasak et al. 2002), their growth (Ramon et al.1981, Unal et al. 2002, Kristina et al. 2001, Dutreux et al. 2000, Matronchik et al. 1996), their orientation (Ignatov et al. 2002, Seelig et al. (1985), protein synthesis (Nakasono et al. 2000), protein activity (Dutta et al. 1994), ATP (adenosine triphosphate) synthesis (Zrimec et al. 2002) and a possible mutation at the genetic level (Nakasono et al. 2004).

In this preliminary study, we investigate the effect of a static 0.5 T magnetic filed on a genetically transformed *Escherichia coli* adhesion and orientation. The adhesion surfaces used are indium tin oxide (ITO) and glass plates. The results of this study point to a new pathway to *E.coli* adhesion inhibition and therefore biofilm formation restrction.

2. Material and methods

2.1. Bacterial strain and growth conditions

The hyper-adherent and fluorescent *E. coli* K-12 strain PHL969, mutant derived from MG1655 d'*Escherichia coli* K-12 strain and containing the pGFP plasmid bought from Clontech, was used according to a previous study of Lejeune (2003). It's a bacterium with an important adherence property thanks to the fusion of curli (adhesion fimbrae) and a plasmid referred to as *p*GFP (it's a plasmid containing a gene of resistance to ampicillin and a gene coding for the "Green Fluorescent Protein" of *Aequorea Victoria* medusa). This strain was cultivated overnight at 29°C in Luria Bertani medium (LB). Then, 0.1 ml of the culture was inoculated into 1:2 diluted LB (½ LB) medium (0.1 ml strain PHL 969 +

2.5 ml ½ LB + 2.5 ml sterile water) in a 18 mm diameter test tube and incubated, with the ITO-coated glass, at 29°C at 45 strokes per minute (spm) for 24 hours before exposure to 0.5 T magnetic field for 30 min. Therefore, the bacteria used are in the stationary growth phase.

The LB medium used contains (per liter of distilled water, pH 7): 10 g tryptone, 10 g yeast extract and 5 g NaCl, and cells reached a concentration of 10^9 per milliliter. The conductivity of this medium is σ = 19.2 mS/cm. Three test tubes containing cells, medium and the substrate were prepared, as cited above, and used as follow: one test tube for the application of a parallel magnetic field (whose direction of the induction **B** is parallel to the surface where bacteria are adhered), the second test tube for exposure to a perpendicular magnetic field (with direction of the induction **B** perpendicular to the adhesion surface), and the third test tube for control (no magnetic field applied). Note that the direction of the lines of magnetic flux is always parallel to the laboratory ground, only the plate positions within the test tubes were changed so that the lines of magnetic flux are perpendicular or parallel to the adhesion surface.

2.2. Abiotic surface preparation for E.coli colonization

Glass substrates (1 cm^2) coated with 110 nm thick semiconductor indium tin oxide (ITO) films (Resistance<20Ω/cm^2) were used in this study (purchased from Merck Display technologies). Before bacterial culture, the plates were previously cleaned by ultrasonication, twice in 2% Fluka cleaning (ref 61257) solution for 30 min and then twice in ultrapure water (Millipore-Q-Systems: R>18 MΩ/cm) for 30 min. Each sonication step was followed by 10 rinsing cycles in ultrapure water (Tlili et al. 2003). The probes were dried under a nitrogen flow; UV sterilized (UV lamp 254 nm, 60 W, Bioblock, France) for 10 minutes and finally plunged into the test tube with the *E. coli* suspension cultivated under the conditions described above.

2.3. Magnetic field application

Cells were exposed to a static magnetic field (SMF) for 30 min as specified at laboratory temperature (about 25°C). A continuous magnetic induction of 0.5 T, in the horizontal direction with the ground, was applied using Helmholtz coils powered by a regulated DC power supply and the magnetic induction was measured using a Hall Effect probe Gauss-meter (Lakeshore 410 Gauss-meter). The test tube containing the colonized surface was placed between the air-gap and oriented in such a way that the surface will be exposed to a perpendicular (or parallel) magnetic field (Fig.1). At the end of exposure, a thermometer was plunged into the *E.coli* suspension to control change in temperature near the sample during the exposure to the magnetic field.

In order to verify the homogeneity of the applied magnetic field (MF), the electromagnetic system has been simulated using Flux3D (Finite Element electromagnetic software - CEDRAT) (Fig.2).

Indeed, to check whether the colonized surface has been exposed to a homogeneous magnetic field, the experimental system (magnetic core, coils and air gap) has been simulated for an arbitrary value of the excitation current. The simulation has been performed with the only purpose to check that exposure field is homogeneous (i.e. to obtain the spatial distribution of the field), and not to compute the precise value of the intensity of the magnetic field, which has been experimentally measured by a Gauss-meter. A constant value of the exposure field has been observed in the area where the colonized surface was exposed to the magnetic field which means that the applied magnetic field is homogeneous (Fig.3). For this type of exposure, variations of the earth's magnetic field were not taken into account because they are negligible compared to the applied magnetic field.

2.4. Bacterial observation and quantification

Exposed and control (non exposed to the magnetic field) *E. coli* K-12 strain PHL969 were observed using a fluorescence microscopy (Axiovert 40 CFL, Zeiss) and photographs were stored for an eye counting of the adhered bacteria. The colonized probe was emerged from the test tube after 30 min of exposure to magnetic field, then placed on microscope coverslip and kept out for an airing during 10 to 15 min before observation under microscope.

Escherichia coli K-12 strains PHL969 are derivatives of *E. coli* K-12 MG1655 strains which contain the pGFP plasmid. The green fluorescent protein plasmid pGFP is involved in the fluorescent character of the *E. coli* strain used in this study. It's a 3.3 kb plasmid with a gene of resistance to ampicillin and a gene coding for the "Green Fluorescent Protein" of *Aequorea Victoria* medusa. This last gene is inserted into the plasmid under the control of a conductive promoter (P_{lac}) but the basic expression level is so high that fluorescent is visible under fluorescent microscopy in every culture conditions in absence of induction.

Green fluorescent protein (GFP) is an autofluorescent protein characterized by two absorption frequency bands: 397 and 475 nm. It's excitation at these wave lengths generates a typical green fluorescence emission with a peak of 508 nm.

Bacterial adhesion and orientation analysis were made by the use of the counting method presented in Fig.4. Bacteria orientation was classified according to three angle values: 45°, 90° and 180° toward the dashed arrow in Fig. 4. This fictitious line was drawn with respect to the probe's position into the test tube while exposed to the magnetic field in order to have photographs representative of the colonized surfaces exposed to magnetic field.

2.5 Statistical Analyses

Data was statistically analyzed using the SAS statistical package, version 9.1 for Windows (SAS, 1996. Differences in mean values for surface were examined with t-test. Analysis of

variance (ANOVA) using the General Linear Models procedure with Duncan test and least significant-difference (LSD). Differences of $P<0.05$ were considered statistically significant. All of the results are expressed as the means ± S.D.

The equation of the model is:

$$Y_{ijk} = \mu + S_i + F_j + S*F_{ij} + e_{ijk}$$

Where:

Y_{ijk}= measured variables, μ= means value of measured variables, S_i= fixed effect of Surface (i= 1 and 2), F_j= fixed effect of magnetic field (j= 1, 2 and 3), $S*F_{ij}$ = fixed effect of the surface inside magnetic field ij= 1, 2 and 3) and e_{ijk}= residuals.

3. Results

We exposed *E. coli* bacteria, previously adhering on indium tin oxide (ITO) semi-conducting surface and glass plate, to a 0.5 T static magnetic field. Data show a significant decrease ($p< 0.0241$) in cell adhesion after exposure to magnetic field compared to the control. Cell adhesion is depending on the surface type (glass or indium tin oxide (ITO)) and on direction of magnetic induction toward the colonized surface (parallel or perpendicular). No significant change observed in temperature near the sample during the exposure to the magnetic field.

Each experiment was repeated four times, and reproducibility was confirmed.

As can be seen in figure 5, before exposure to magnetic field (MF), we noticed more adhered cells on glass than on indium tin oxide (ITO). However, after exposure we observed a decrease in the number of adhered bacteria on both surfaces with an evident dependence on the direction of the magnetic induction towards the surface colonized by the cell (Fig.5).

Indeed, our results revealed more adhered cells after exposure to a perpendicular magnetic field (MF) with a tendency to adhere more on indium tin oxide (ITO) surface. On the other

hand, we found nearly the same adhered cells number in both surfaces under parallel magnetic field (MF).

In order to quantify the relative effect of magnetic field on surface decolonization, the rate of decolonized bacteria D (%) = 100 × (N_0 – N)/N_0, where N_0 represents the number of adhered bacteria before exposure to magnetic field, and N represents the number of adhered bacteria after exposure.

A summary of the surface decolonization rate, representing a decrease in the number of adhered bacteria, is reported in Fig.6.

Cell detachment depends on surface and magnetic field types for the same bacteria strain (*E .coli*). Data show a positive decolonization rate, on both glass and ITO substrates, after exposure to parallel magnetic field (ITO-parallel MF and Glass-parallel MF).

Indeed, one can observe more detached cells (decrease in the number of adhered bacteria), on both surfaces after exposure to parallel magnetic field (ITO-parallel MF and Glass-parallel MF) and a small effect after exposure to perpendicular magnetic field in the case of indium tin oxide (ITO-perpendicular MF). Thus, according to these results we can conclude that exposure to parallel magnetic field (MF) has better effect on *E. coli* decolonization from indium tin oxide (ITO) and glass than exposure to perpendicular magnetic field.

Results on cell orientation analysis indicate that there was a significant decrease in the number of bacteria adhering on indium tin oxide (ITO) and oriented perpendicularly (90°) to the lines of magnetic flux, and after exposure to parallel magnetic field compared to the control (Fig.7).

However, no effect has been reported ($p<0.0812$) and no difference ($p<0.0785$) with non exposed cells has been found for glass. Surprisingly, no significant effect was observed

after exposure to perpendicular magnetic field (MF) and we observed practically the same orientation attitude and number of oriented cells as in the control assay.

4. Discussion

These results show a clear effect of 0.5 T homogeneous magnetic field on *E.coli* adhesion on a semi-conductor indium tin oxide (ITO) and glass surfaces. Indeed, our data provided evidence that *E. coli* adhesion depends on the surface type and on the direction of the magnetic induction **B**. Exposure to magnetic field decreased the number of adhered cells compared to the control samples (before exposure). Moreover, there were more adhered cells after exposure to perpendicular magnetic field than to parallel magnetic field (see Fig.5).

Furthermore, we evaluated *E.coli* decolonization rate after exposure to magnetic field and we found that cell detachment depends on surface and magnetic field types for the same bacteria strain (*E.coli*). In fact, we observed a positive decolonization rate on both glass and ITO substrates after exposure to parallel magnetic field (see Fig.6). However, one can observe the small decolonization effect of perpendicular magnetic field on *E. coli* adhering to ITO.

Magnetic field didn't affect cells oriented parallel (180°) to the magnetic induction at both surfaces (see Fig.7). There was no significant difference in comparison with control samples. Furthermore, no magnetic field effect shown on cells oriented 45° with the direction of the magnetic induction, which seems to be the preferential orientation for *E. coli* on solid surfaces. However, the number of cells oriented perpendicularly (90°) to the direction of the magnetic induction has decreased up to the half, after exposure to parallel magnetic field in the case of indium tin oxide.

As indium tin oxide and glass plates have different chemical compositions and physical properties, we can conclude that these observations are in agreement with the prediction of

Andrade et al. (1983), suggesting the dependence of cell adhesion on the physico-chemical properties of the surface. One can see that there probably have been stronger physico-chemical interactions (electrostatic, Van Der Waals, hydrogen bonds…) which took place between *E. coli* and indium tin oxide surface after application of perpendicular magnetic field. Hydrodynamic interactions cause the extended interaction of cells and with surfaces (Ramia et al. 1993).

It's known that magnetic force **F** acting on a moving charge has a magnitude given by Crowell (2002):

$$|\boldsymbol{F}| = q|\, v \,||\, \boldsymbol{B} \,|\, \sin \boldsymbol{\theta}$$

Where $\boldsymbol{v}$ is the particle velocity vector, $\boldsymbol{q}$ represents its charge and $\boldsymbol{\theta}$ is the angle between the $\boldsymbol{v}$ and **B** vectors. The force is always perpendicular to both $\boldsymbol{v}$ and **B**. Given two vectors, there is only one line perpendicular to both of them, so the force vector points in one of the two possible directions along this line. Therefore, this theory may explain the differences in *E. coli* adhesion and orientation found after exposure to perpendicular and parallel magnetic fields.

The homogeneity or inhomogeneity of magnetic field has been shown to play a role in bacterial adhesion on surfaces. Indeed, many studies had mentioned different effects of 5.2-6.1 T inhomogeneous high magnetic fields (Horiuchi et al. 2001), and 3.2-6.7 T inhomogeneous, 7 T homogeneous magnetic fields on *E. coli* viability (Tsuchiya et al. 1996). In this study, the colonized surfaces have been exposed to a homogeneous magnetic field.

Tsuchiya et al. (1996) presume that 7 Tesla (T) magnetic field affects the cells of the bacterium differently, depending on the growth phases. Indeed, it is known that cells contain many components and factors which are oversensitive to high magnetic fields such as ion solutions, water (Ueno et al. 1994), macromolecules (e.g. proteins), lipids in

membrane (Speyer et al. 1987) and nucleic acids (Maret et al. 1975). Since the extracellular substances and chemical conditions in the culture broth are constantly changing and thus giving rise to metabolic differences between logarithmic and stationary phase cells, it is believable that high magnetic field's effects on bacteria differ, depending on the bacterium growth phase. In this study, bacteria were used at the stationary phase.

The aim of the present research was to study 0.5 T homogeneous magnetic fields on *E.coli* adhesion and orientation. Other studies were performed to see possible effects on gene expression and DNA. For this purpose, Potenza et al. (2004) concluded that 300 mT static magnetic field can influence cell growth and gene expression. They speculated that it can perturb DNA stability interacting with DNA directly or potentiating the activity of oxidant radicals. Ikehata et al. (1974) examined possible mutagenic and co-mutagenic effects of strong static magnetic fields using the bacterial mutagenicity test. No mutagenic effect of static magnetic fields up to 5T was detected.

In our study, the existence of an important number of adhered cells under a perpendicular magnetic field (compared to the number under parallel magnetic field) may be due to the exposure duration. Probably, 30 min of exposure were not sufficient for bacterial desorption in these experimental conditions. Whereas, it should be a sufficient period of time to enable parallel magnetic field to modify the physico-chemical properties of the cell-surface interface.

In the literature, it has been shown that an applied magnetic field at a well-defined strength needs certainly precise exposure duration to have an effective effect (Ishizaki et al. 2001, Belyaev et al. 1998). In other words, each magnetic field strength has its own effective exposure duration. Thereby, the magnetic field strength and the exposure time are significant parameters in cell response to magnetic stress. Strasak et al. (2002) think that

the effect of 2.7-10 mT magnetic fields on cells may be due to a change in the ion transport into the cells and a possible formation of free radicals after the exposure to magnetic field.

Binhi et al. (2001) suggested that DNA transcription and conformation state are of a great interest in the effect of magnetic field on *E. coli*. They concluded that magnetic field could affect the dissociation probability of some ions and ion-protein attached to the DNA strands which are rotating at a low speed.

According to Harshey (2003), the motion of bacteria close to surfaces is relevant to understanding the early stages of biofilm formation and of pathogenic infection. For this purpose, we studied the orientation of bacteria adhering on indium tins oxide (ITO) and glass surfaces after exposure to magnetic field.

Frymier et al. (1995) presume that individual *E. coli* cells swim in clockwise, circular trajectories near planar glass surfaces. Moreover, according to Vigeant and Ford (1997), bacteria swim in circles at surfaces for seconds to minutes, although one can expect them to drift from the surface quickly because of the effects of the rotational Brownian motion and bundle fluctuation on their trajectories. Lowe et al. (1987) studied the element responsible for *E. coli* movement. Indeed, they assume that classical example of rotation in *E. coli* is a rotary flagellar motor. According to these authors, several filaments come together to form a bundle that rotates at a speed around 300 revolutions/sec (rps) and drives the cell body forward at speeds of a few tens of microns per second. The cell body counter-rotates at several rps. Therefore, when a cell swims close to a planar surface, the flagellar bundle and the cell body rotations as well as surface resistance (roughness, heterogeneity) affect the direction of movement (Diluzio et al. 2005).

Prigent-Combaret et al. (1999) suggested that cell-to-cell signals may be involved in regulation of gene expression. Hence, cell density seems to be an important parameter for

bacterial adhesion on solid surfaces and thus for their orientation under external stress agent.

One can conclude that magnetic field effects on the behaviour of bacteria depend also on the bacterial strain, the induction values and on the exposure time.

Conclusion

Regarding the results reported in the present study, one can conclude that 0.5 T magnetic field have an effect on *E. coli* adhesion and orientation. Indeed, our data revealed different effects depending on the surface and on the direction of the magnetic induction toward that surface. Moreover, there were more adhered cells under perpendicular magnetic field than under parallel magnetic field. Cell orientation was affected especially under parallel magnetic field. Summarizing, 0.5 mT magnetic field can be used to stimulate *E. coli* desorption while adhering on indium tin oxide and glass surfaces, and therefore may constitute an important and useful pathway for *E.coli* adhesion inhibition and therefore biofilm formation restriction.

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Conflict of interest

No conflict of interest declared

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Figure captions

Fig.1. Schematic view of the apparatus for magnetic field exposure.

Fig.2. Geometry of the exposure device.

Fig.3. Simulation of the magnetic flux density (in Tesla) in the air-gap of the magnetic field exposure system by Flux 3D software.

Fig.4. Schematic illustration of the counting method used in cell adhesion analysis.

Fig.5. Dependence of *E. coli* adhesion on the surface type and on direction of magnetic induction.

Fig.6. Surface *E. coli* decolonization rate after exposure to magnetic field

Fig.7. *Escherichia coli* orientation toward the magnetic induction.

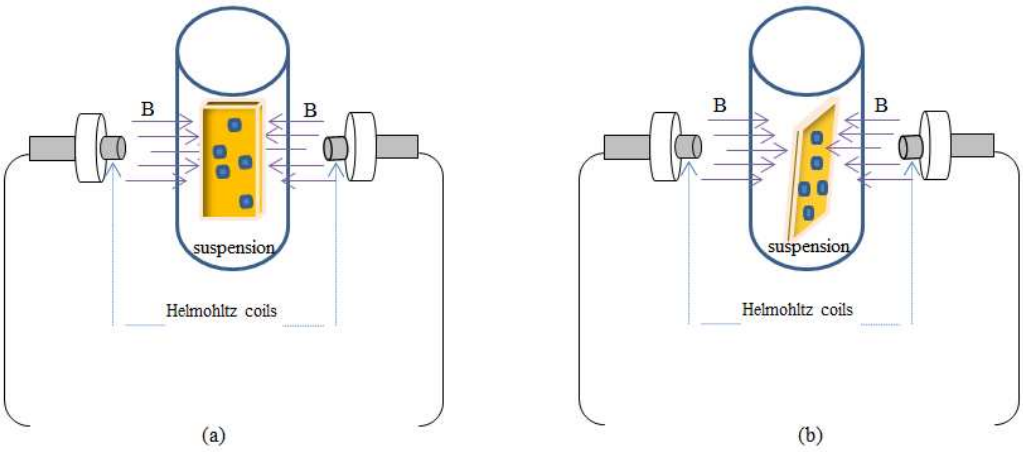


Fig.1. Schematic view of the apparatus for magnetic field exposure

Horizontal arrows show the direction of the induction (**B**) of the applied magnetic field.The colonized substrate position in the test tube is choosen in such a way that lines of magnetic flux arrive parallel (a) or perpendicular (b) to the sample surface.

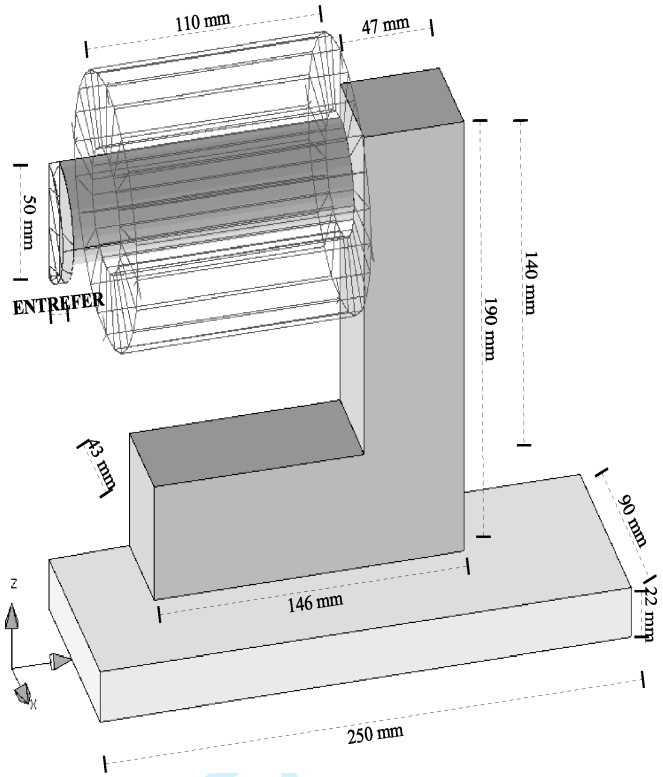


Fig.2. Geometry of the exposure device modelled by Finite Elements using the commercial software Flux3d (only a quarter of the geometry is represented)

This system is composed of a steal core, an adjustable air-gap and two excitation coils, which have been supplied by a continuous current.

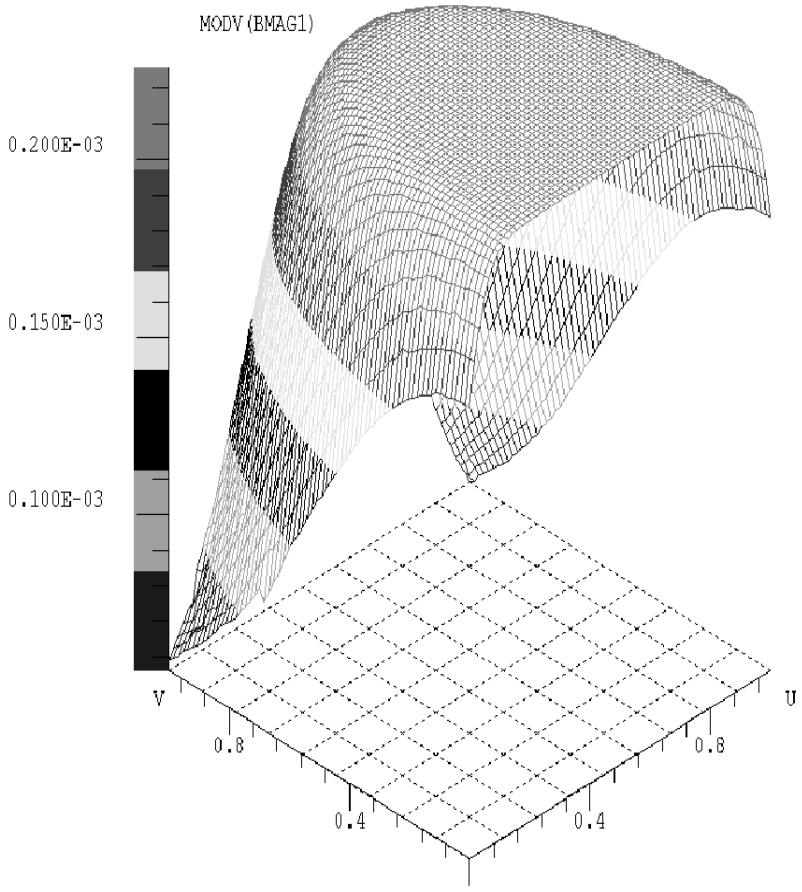


Fig.3. Simulation of the magnetic flux density **B** (in Tesla) in the air-gap of the magnetic field exposure system by Flux 3D software , (air-gap = 18 mm represents the test tube diameter containing the cell medium and the sample). The spatial distribution of the magnetic flux density **B** in the middle of the air-gap is plotted (only half of the geometry is plotted). One observes a constant value of **B** in the area corresponding to the tube section which confirms that the colonized surface has been exposed to a homogeneous field. The axis units are normalized to 1.

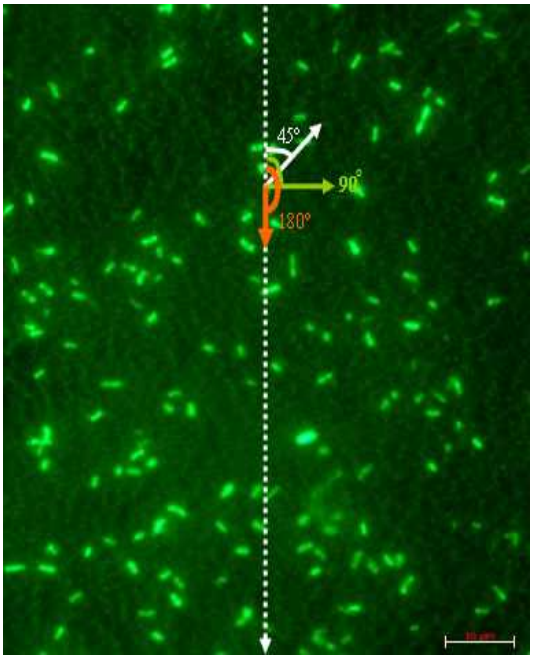


Fig.4. *Escherichia coli* bacteria (in green fluorescent) photography showing the counting method for the orientation study

Bacteria having an angle of 45°, 90° and 180° towards the fictitious line (dashed arrow) were counted. Note that for the scale, the bar (2 cm) represents 10 µm.

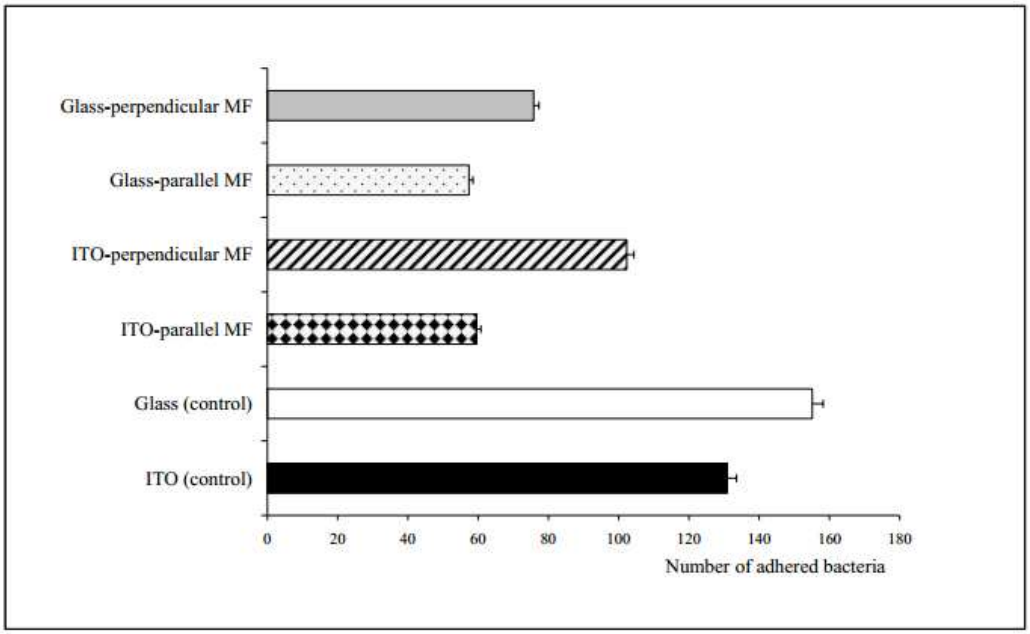


Fig.5. Dependence of *E. coli* adhesion on the surface type and on the direction of the magnetic induction **B**. Exposure to magnetic field decreased the number of adhered cells. We note more adhered cells after exposure to the perpendicular magnetic field than to parallel magnetic field compared to the control samples.

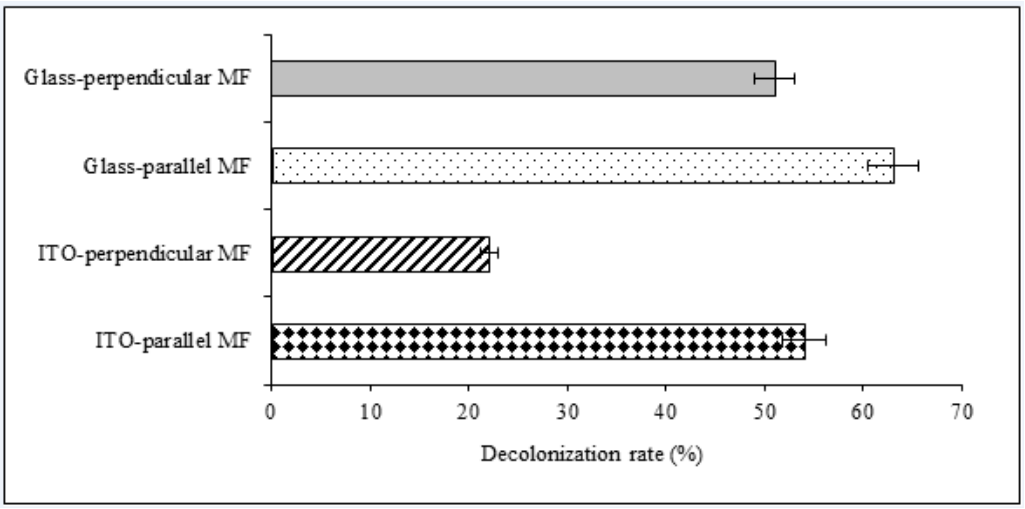
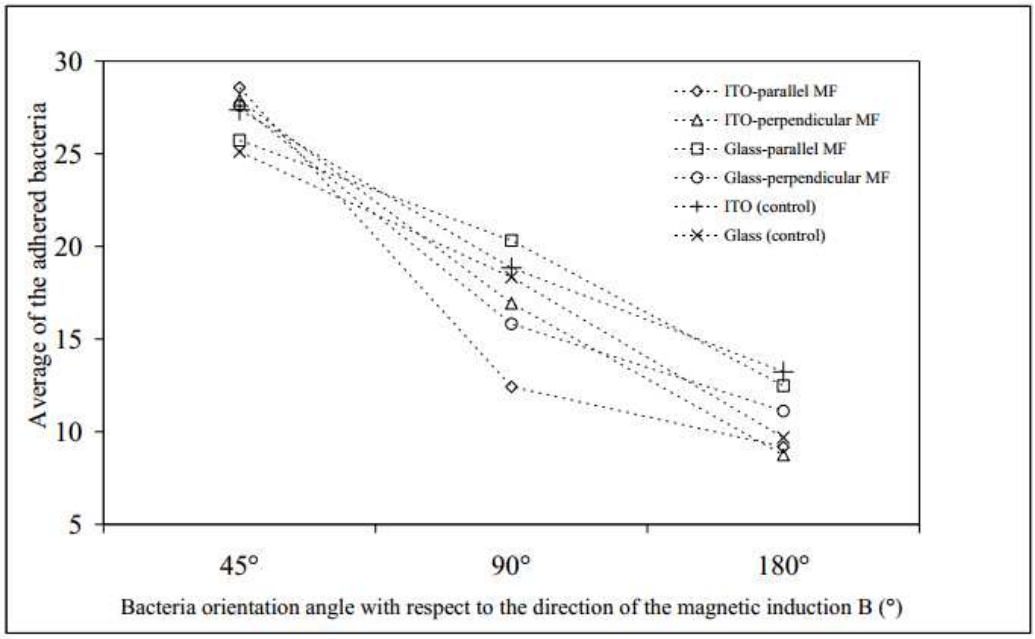


Fig.6. Surface *E. coli* decolonization rate after exposure to magnetic field

ITO-parallel MF, Glass-parallel MF, and ITO-perpendicular MF, Glass-perpendicular MF represent the indium tin oxide (ITO) and glass colonized surfaces exposed to parallel and perpendicular magnetic field, respectively.

Cell detachment depends on surface and magnetic field types for the same bacteria strain (*E .coli*). Data show a positive decolonization rate, on both glass and ITO substrates, after exposure to parallel magnetic field (ITO-parallel MF and Glass-parallel MF). However, one can observe the small decolonization effect of perpendicular magnetic field on *E. coli* adhering to ITO (ITO-perpendicular MF).



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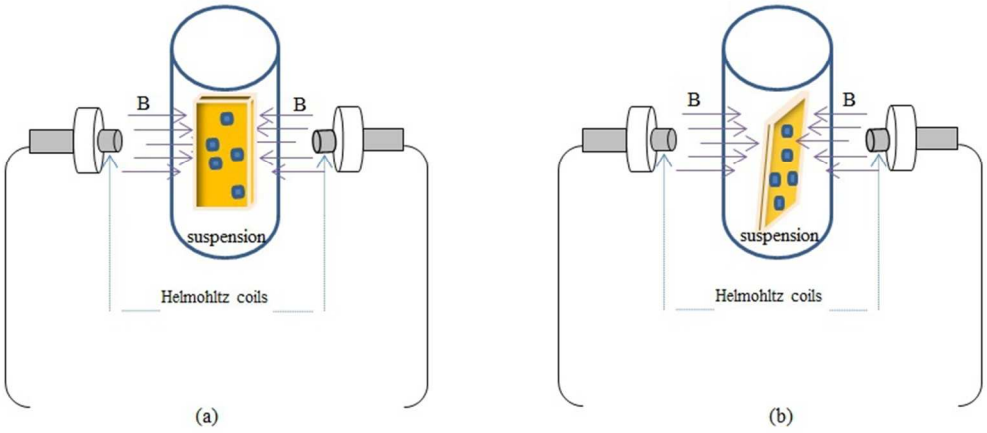

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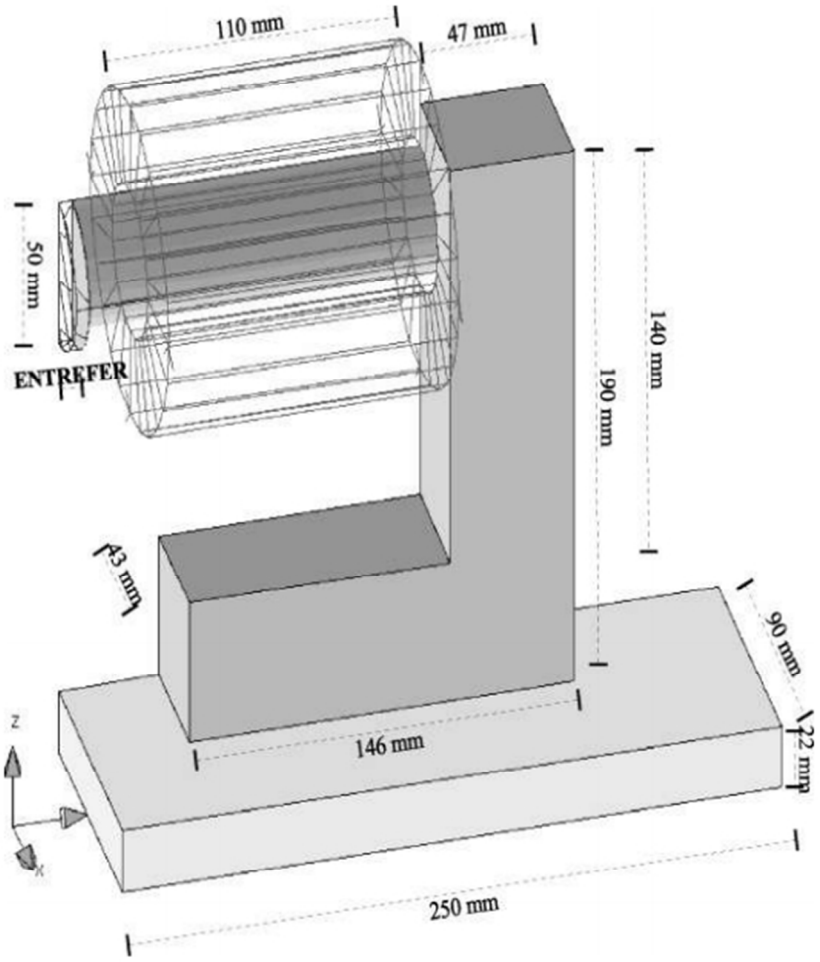
Horizontal arrows show the direction of the induction (B) of the applied magnetic field.The colonized substrate position in the test tube is choosen in such a way that lines of magnetic flux arrive parallel (a) or perpendicular (b) to the sample surface.

218x110mm (96 x 96 DPI)



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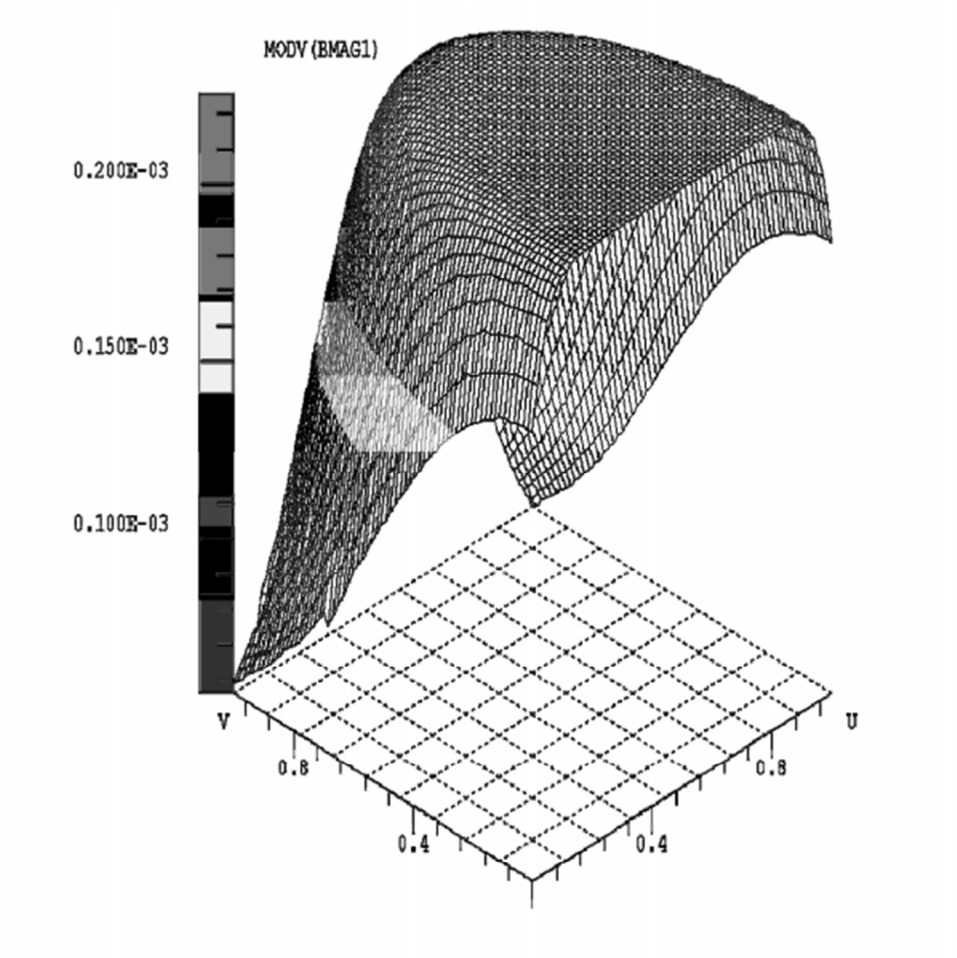
This system is composed of a steal core, an adjustable air-gap and two excitation coils, which have been supplied by a continuous current.

172x169mm (96 x 96 DPI)



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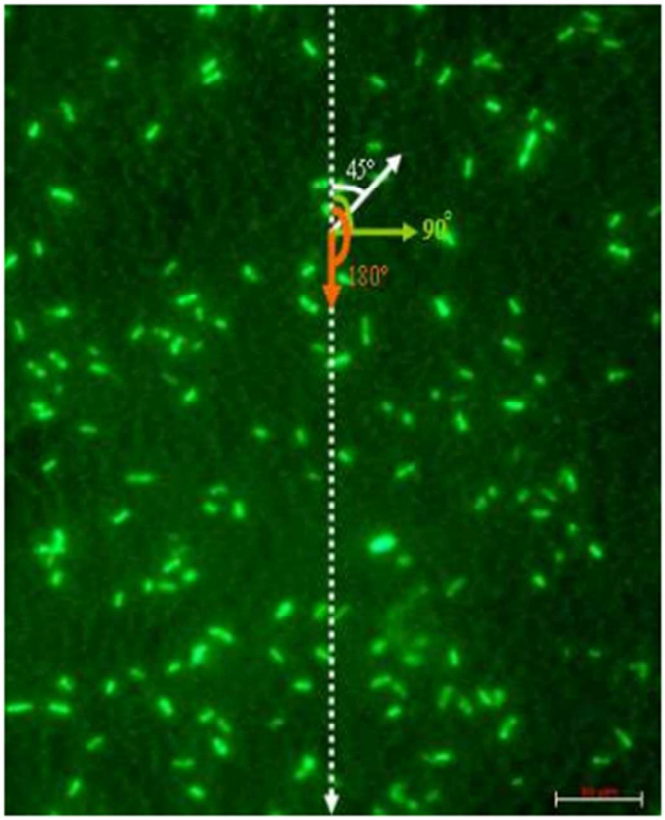
165x160mm (96 x 96 DPI)



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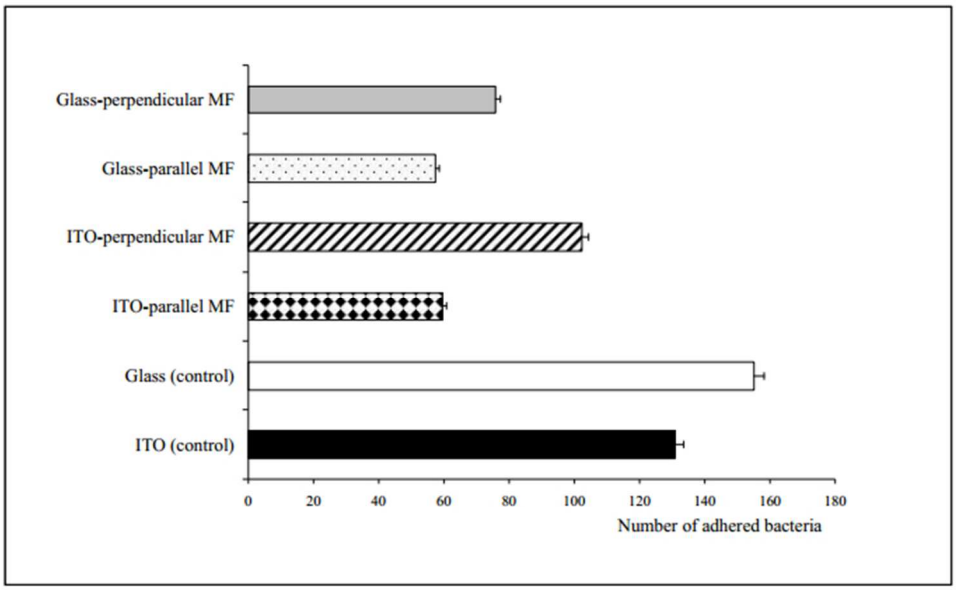
127x127mm (96 x 96 DPI)



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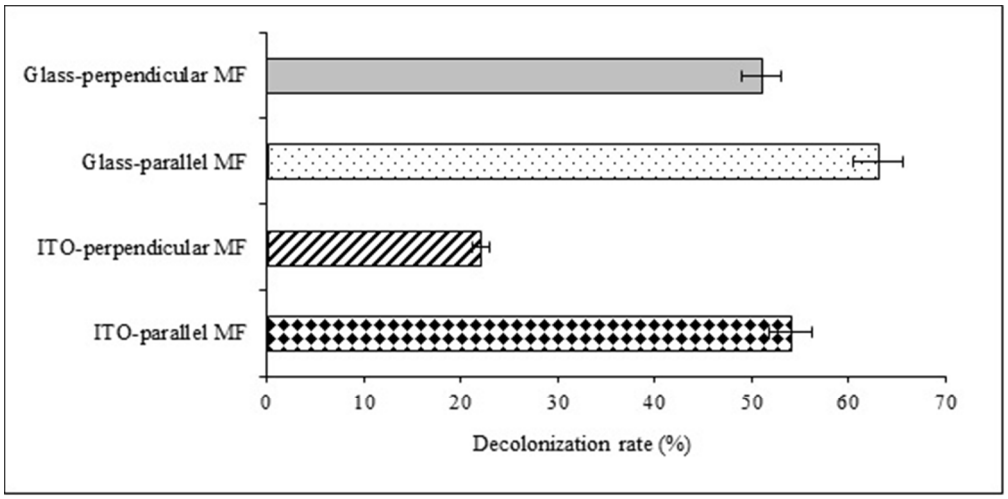
189x118mm (96 x 96 DPI)



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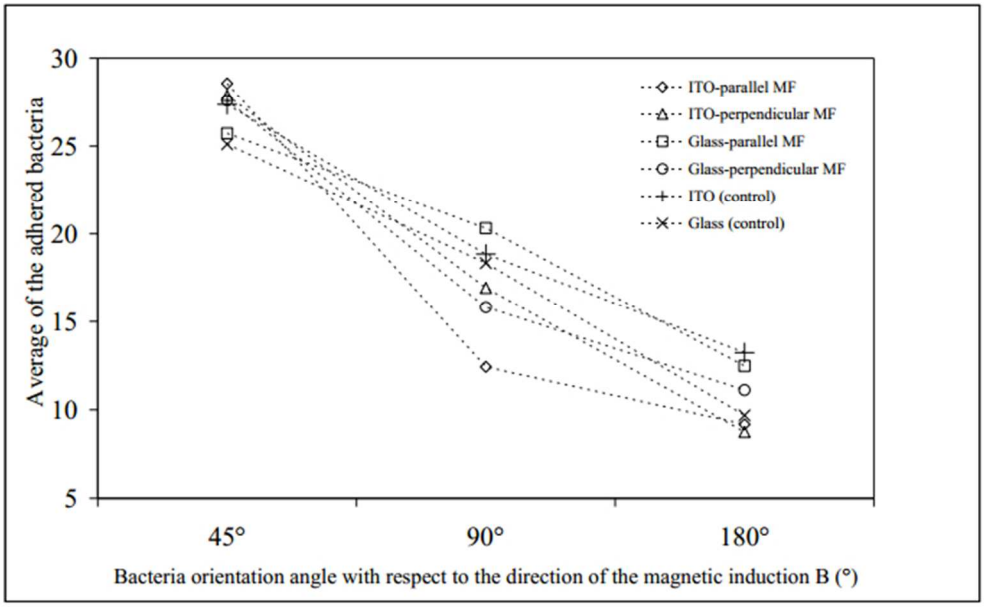
154x75mm (96 x 96 DPI)



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183x114mm (96 x 96 DPI)