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Determination of Critical Relative Humidity of Construction Materials for Mold Growth by Experimental Study

Deneysel Çalışma ile Küf Büyümesi için Yapı Malzemelerinin Kritik Bağıl Neminin Belirlenmesi

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Abstract

Resistance of materials to mold fungi is directly related to the material properties and the environmental temperature and relative humidity level. Critical relative humidity occurs when the relative humidity reaches to the point where mold fungi can grow on the substrate. A strategy should be developed to address the conditions of mold fungi growth and use more suitable materials depending on the humidity conditions in the building. The purpose of this research was to establish the essential relative humidity of various construction materials based on their substrate category in order to get a better understanding of mold resistance and to reduce the danger of mold development. The critical relative humidity for six building materials was determined in this research to assess each substrate category's resistance to mold growth. Inoculation of construction materials with six mold spores (*Penicillium, Cladosporium, Chaetomium, Scopulariopsis, Aspergillus, and Acremonium*) and incubation in a desiccator at 22° C (%75-95). For 3 months, samples were analyzed once a week. Mold growth was most sensitive to substrate category I (gypsum board) in this laboratory experiments. There was no evidence of growth in any of the glass or composite samples. The essential moisture level varied according to substrate category. For example, the essential humidity level for drywall (category I) was 80%, whereas for rock wool it was 85% (category II). At various relative humidity levels, the time needed for critical mold development varied. Critical mold development times for gypsum board are 12 weeks at 75% relative humidity and 1 week at 95% relative humidity. The greater the environment relative humidity, the less time essential mold development requires on the substrate.

Keywords: Mould, Relative humidity, Critical relative humidity level, Building material, Mould resistance

Öz

Yapı malzemelerin küf mantarlara karşı direnci, malzeme özellikleri, ortam sıcaklığı ve bağıl nem seviyesi ile doğrudan ilişkilidir. Kritik bağıl nem, bağıl nem, substrat üzerinde küf mantarlarının gelişebileceği noktaya ulaştığında meydana gelir. Küf mantarlarının üreme koşullarını ele almak ve binadaki nem koşullarına bağlı olarak daha uygun malzemeler kullanmak için bir strateji geliştirilmelidir. Çalışmada yapı malzemelerinin küf direncini daha iyi anlamak ve küf oluşumu riskini en aza indirmek için substrat kategorisine bağlı olarak kritik bağıl nemini belirlenmesi amaçlanmıştır. Bu çalışmada, her substrat kategorisinin küf oluşumuna karşı direncini değerlendirmek için altı yapı malzemenin kritik bağıl nemi belirlendi. Yapı malzemeleri altı küf sporu (*Penicillium, Cladosporium, Chaetomium, Scopulariopsis, Aspergillus ve Acremonium*) ile aşılandı ve 22°C'de (%75-95) bir desikatörde inkübe edildi. Üç ay boyunca numuneler haftada bir kez analiz edildi. Laboratuvar testlerinde, küf oluşumuna en duyarlı, substrat kategori I (alçı levha) olmuştur. Cam ve kompozit numunelerinin hiçbirinde üreme tespit edilmedi. Kritik nem seviyesi farklı substrat kategorileri için farklıydı. Örneğin, alçıpan (kategori I) için kritik nem seviyesi %80, taş yünü için (kategori II) ise %85 idi. Farklı bağıl nem seviyelerinde kritik küf gelişimi için gereken süre değişiklik göstermiştir. Bu kapsamda alçı levha için kritik küf gelişimi %75 bağıl nemde 12 hafta, %95 bağıl nemde ise bir haftadır. Ortamın bağıl nemi ne kadar yüksek olursa, substrat üzerinde kritik küf oluşumu için gereken sürenin o kadar kısa olduğunu göstermektedir.

Anahtar Kelimeler: Küf, Bağıl nem, Kritik bağıl nem seviyesi, Yapı malzemesi, Küf direnci

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1. Introduction

Mold fungi have a high resistance to adverse conditions as well as a high ability to produce spores. As a result, fungal spores can be found in any environment and on any surface. Mold fungi are an integral part of the ecosystem because they are responsible for the separation and recycling of dead matter. Indoor mold fungi, on the other hand, can be harmful to people's health as well as damaging to building materials and components. Therefore, measures should be taken to prevent the growth of fungi in these environments. It is important to know the factors that affect the growth of fungi in order to prevent the growth of indoor fungi (Johansson 2018, Nielsen 2004, Sedlbauer 2002, Adan 1994). Mold growth is greatly influenced by a number of important factors, including humidity, temperature, and substrate. Mold fungi must be exposed to these elements for a specific period of time. Generally, moisture is the most important factor in mould growth. Moisture requirements for mould growth are temperature- and nutrient-dependent(Stanaszek-Tomal 2020, Jugles et al. 2020, Moon 2005, Stanaszek-Tomal 2020, Jugles et al. 2020,).

The more closely the temperature and nutrient content are to their optimal values, the less moisture is required for growth (Wu and Wung 2020, Johansson 2018, Sedlebauer 2004, Adan 1994, Ayerst 1969). The amount of moisture required for fungi growth is determined by the moisture content of the substrate on which they grow. This quantity of moisture is referred to as relative humidity (Sedlebauer 2004, Moon 2005, Samson et al. 2001, Adan 1994). In each material, the rate of fungal growth varies. Some materials can tolerate high humidity without mold development, whereas others cannot withstand mold growth even at low humidity levels.Many studies have been conducted to determine the environmental parameters that induce mold development in various construction materials (e.g. Hofbauer et al. 2008, Nielsen 2004, Nielsen 2002, Ritschkoff et al. 2000, Viitaneu 1998). One should anticipate that humidity and temperature levels inside a building will fluctuate. The preferred materials to reduce the risk of mold growth should be those that can withstand the current conditions. Due to the diversity of construction material, it is impracticable to assess their resistance to microbial growth. Following a review of the literature, three substrate categories were proposed to assess the effects of the substrate on mold growth (Doll and Burge 2001, Horner et al. 2001, Klamer et al. 2004, Nielsen 2004, Pasanen et al. 2000).

The purpose of this study was to determine the critical relative humidity of the substrate in order to gain a better understanding of the mold resistance of building materials and to facilitate the selection of an appropriate material for the anticipated temperature and relative humidity conditions in order to minimize the risk of mould growth.

2. Material and Method

2.1. Fungal Species

Mold fungi species found in various climates vary considerably (Andersen et al. 2011, Hyvärinen et al. 2002). Therefore, we selected mold fungi found in buildings of the Mediterranean climate. As a result, an apartment with dampness and mold issues was chosen in Istanbul's Avcılar district. The samples were collected from locations contaminated with molds. The samples were cultured on malt agar in Petri dishes until sporulation occurred. To identify the fungal species, the samples were examined in Istanbul university Medical Microbiology laboratory. These species frequently exhibit a wide range of water requirements (Grant et al. 1989) and belong to distinct groups in terms of successional colonization. These fungi species were mixed together to replicate real condition (Table 1).

2.2. Building Materials

Due to the diversity of building materials, it was difficult to assess them separately. This could be simplified by classifying materials as according ones resistance to fungal. Sedlebauer (2002) proposed four categories of substrates based on experimental examinations to account for the influence of the substrate on the formation of mould fungus (Sedlbauer 2002). Various building materials were assigned to each of the four substrates in order to support this purpose. Substrates categorized as optimal culture medium, biologically recycled building materials, porous building materials, and non-degradable and nutrient-free building

Table 1. Mould species used.

Species	Growth Conditions			
	Temperature (°)		Relative Humidity (%)	
	Min.	Opt	Min.	Opt
Penicillium	5	25	78	-
Cladosporium	-5	25	85	-
Chaetomium	5	26	-	-
Scopulariopsis	-	25	-	-
Aspergillus	10	35	-	-
Acremonium	-	26	77	-

Table 2. Material type and Substrate Categories.

Material	Material description	Substrate Category
Plasterboard	12.5 mm standard cardboard covered gypsum.	I
Rock wool	Made of 30 mm rockwool, uncoated yellow and black glass wool on both sides.	II
Water-based paint	Acrylic compolymer-based, silicone-added, water-based interior wall paint.	II
Solvent based paint	Contains anticorrosive and zinc chromal pigment. Interior wall paint.	II
Glass	2mm standard window glass	III
Composite	Aluminum composite facade panel.	III

materials. Because this study was limited to building materials, only categories I, II, and III were considered. This was accomplished by selecting materials from each category (Table 2). Without contamination, mold fungi could not be formed on substrate category III. There were a high risk of fungal growth on items in categories I and II, depending on the environmental conditions in which they were located. In this study, different construction materials were determined for each substrate type. Based on their frequency of usage in the envelopes of Istanbul buildings, six building elements were ultimately selected for this purpose. All materials were purchased from a local shop and divided into four 50 x100 mm test pieces. The test pieces were located at 22° C and relative humidity levels ranging from 75 % to 95 % were applied. Additionally, all materials were sterilized on their surfaces prior to use.

2.3. Suspension of Fungal Spores

To ensure that each test was repeatable, a spore suspension was produced in a standardised manner, mostly in accordance with MIL-STD-810G. (Department of Defense 2010). 45 mL of sterilized water was poured into a culture flask containing crystal beads which was filled with spores that had been scraped off the fungus's surface (building materials laboratory of ITU). A single flask represented each species. To release the spores from the conidiophores, the flask was shaken, which dispersed the spores. Sterile glass wool was used to filter the contents of the flask. After discarding the supernatant, the spores were cleaned with sterilized water. The solution has been then separated by centrifugation as it ever was. This was done three times in order to wash out all the nutrients from the agar. The final spore suspension was made by combining equal volumes of each species' suspension.

2.4. Spore Suspension Inoculation Method

It is critical to achieve fungal growth by inoculating the specimen properly. This can be done in a variety of ways and according to one's personal preferences. The technique of Johansson et al. employed (Johansson et al. 2018). In order to conduct this experiment, a spore suspension of 0,4 ml was applied to one surface of each specimen. The liquid suspension was sprayed onto the surfaces of the test pieces to spread the spores evenly across the surface (building materials laboratory of ITU).

Table 3. Mould growth rating scale for the experiments.

Rating	Description of extent of growth
0	No fungal growth
1	Coverage ≤ 1%
2	1%< Coverage ≤10%
3	10%< Coverage ≤30%
4	30%< Coverage ≤70%
5	70%< Coverage

2.5. Inoculation

The prepared samples were placed horizontally in desiccators. Each desiccator was programmed to maintain 22 ˚C and a desired relative humidity. Each desiccator was equipped with a digital humidity and thermometer for regular temperature and relative humidity control (building materials laboratory of ITU).

2.6. Ambient Conditions of Desiccators

All desiccators were set to maintain a constant 22° C and a relative humidity of %75± 5, %80±5, %85 ±5, %90± 5, and %95± 5, respectively. Silica gel, calcium chloride, and carbonate were used to create desiccators for 80, 85, 90 and % 95 relative humidity, respectively and pumice was used to create %75 (building materials laboratory of ITU).

Three months were spent testing each sample of the selected materials at a constant temperature and specified relative humidity. For 3 months, samples were analysed weekly

2.7. Evaluation of Fungal Growth in Laboratory Samples

Weekly evaluations were conducted on all surfaces of samples exposed to mold growth. The surfaces of the samples were examined for fungal growth using either the

naked eye or a 40x stereo microscope in this evaluation. On the surfaces of the samples, fungal growth was evaluated using the rating scale shown in Table 4. No surface contact was made when the analysis procedure was used, as it was non-destructive (Frühwald et al. 2008). This study method made it possible to continuously monitor mould growth on the same test piece. The results were analyzed on the basis of the simplified judgment. When the mold growth rating reached 2 or higher for the first time, a test piece was considered to have failed.

Table 4. Critical humidity level of materials according to 12 week incubation results (at 22° C).

Material	Relative Humidity(%)
Plasterboard	80
Rock wool	85
Water-based paint	90
Solvent based paint	90
Glass	-
Composite	-

2.8. Definition of Critical Moisture Level

The tests were conducted at a constant relative humidity. The critical relative Humidity was determined by the case with the lowest relative humidity that met any of the preceding criteria. For instance, if the critical mould level requirements were satisfied at a relative humidity of 90%, the critical relative humidity for this material was considered to be 90%.

3. Results

Mold fungi growth was detected in all tested materials after varying exposure times and relative humidity conditions (%75-95 RH and 22°C) in the building materials laboratory of İTÜ -Faculty of Architecture. The growth of mould on plasterboard was detected using the naked eye and the light microscope for the upper and lower sides. The first stage of growth (rating 2) was detected in plasterboard after one week of exposure, and rating 3 was detected after three weeks, depending on the test series (Figure 1).

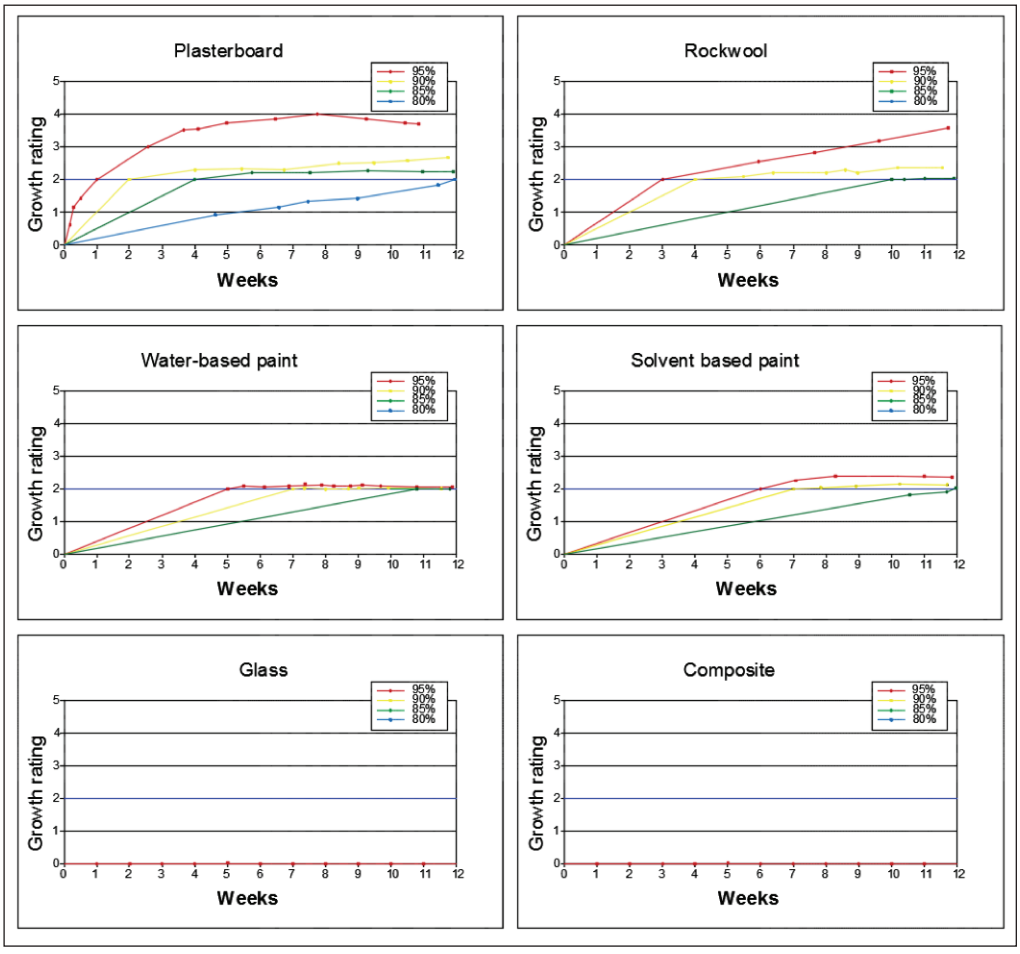

Figure 1. Fungal growth on test pieces of substrate at various relative humidity at 22° C during 3 month.

As the exposure continued, the highest rating for mold growth was detected in plasterboard. The majority of the mold fungi were Penicillium and Aspergillus species. Additionally, the rating 2 was detected in rockwool after three weeks, but only on surfaces in which spore suspension had been sprayed. After five weeks, a first sign of mold growth was detected just on top surface of water-based paint in which spore suspension had been sprayed.

When the exposure time was prolonged, mold growth was detected in all study materials. Numerous thin mould hyphae were discovered in solvent-based paint. The type and intensity of mould growth varied according to the material. In rockwool, dark, hyphae had been bonded to fibers, and the rockwool's solidity appeared to deteriorate over time, affecting its mold resistance (Figure 2). Mold fungi was also very dark on plasterboard (Figure 3).

Under 85% relative humidity, no growth of mold fungi was detected in Category II materials, while growth was detected in Category I materials. No growth was detected in Category III, under any humidity conditions. The results were summarized in Table 4.

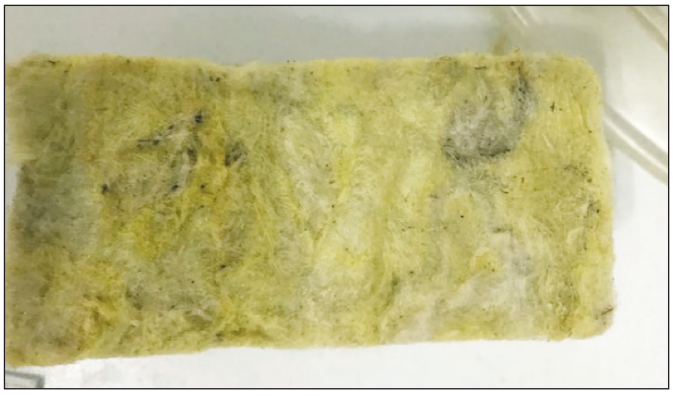

Figure 2. Dark mould fungi on the surface of rockwool.

Figure 3. Dark mould fungi on the surface of plasterboard.

In this study, the time needed for samples to achieve critical relative humidity values is important. When critical mold growth occurs at the lowest possible relative humidity, building materials approach critical relative humidity. The estimated critical relative humidity for the materials tested after 3 months of incubation. During the test, the highest relative humidity was %95 and the lowest relative humidity was %75 (Figure 4). The time required for critical mold growth at specified relative humidity could be determined using this information (Table 5).

The results show that the higher the relative humidity of the environment, the shorter the time required for critical mould growth on the substrate. Mold growth on plasterboard, for instance, takes 12 weeks at a relative humidity of less than 80%, but just two weeks at a relative humidity of 90%. (Figure 4).

Table 5. The required time for the critical relative humidity level of the material (at 22° C).

Material	Required time
Plasterboard	12
Rock wool	10
Water-based paint	11
Solvent based paint	12
Glass	-
Composite	-

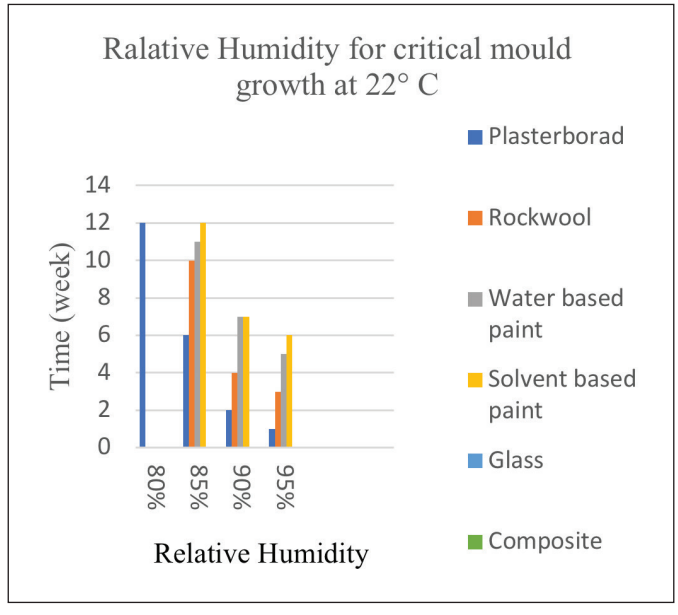

Figure 4. Graph of the time required for critical mould growth. at the specified relative Humidity. (time is determined weekly).

4. Discussion

Numerous laboratory techniques have been developed to determine a material's resistance to mold growth (Adan 1994, Chang et al. 1995, Pasanen et al. 2000, Wang 1992). The technique we employed in this research has certain similarities to and differences from previous methods reported in the literature. Differences may exist in the sensitivity of individual materials to mould, despite belonging to the same group of materials, as well as variations in test setup and analysis techniques.

The duration of the experiment is a critical factor in these studies. The longer the test, the greater the chance of fungal growth. However, for practical reasons, these tests cannot be conducted indefinitely and results must be presented at the appropriate time. According to literature, 12 weeks is an appropriate duration for this method (Johansson et al. 2012, Viitanen 2004). Additionally, the time required for materials to exhibit first signs of fungal growth at critical relative humidity varies (Viitanen et al. 2010). It's worth noting that the higher the relative humidity, the shorter the time required for exposure to other mold-growing conditions. To evaluate a material's critical moisture level, it must be tested at various humidity levels. According to the literature on humidity conditions for fungi growth, the minimum required relative humidity for growth is 75% and the maximum required is 95%(Tsongas et al. 2016, Dedesko and Siegel 2015, Grant et al 1989, Holme et al. 2008). In our study, the relative humidity conditions in the laboratory were determined to be a minimum of 75% and a maximum of 95%.

We examined a combination of spores from six distinct fungus species to simulate the natural habitat (Table 1). As a result, the cumulative effect of these various mold types on the materials was determined. As well, building materials exhibit varying degrees of resistance to mold fungi formation based on their properties. Due to the varied resistance of construction materials, this study investigated three distinct categories. Moreover, to determine the relative humidity of building materials, samples from each category were chosen.

Environmental factors have an effect on the critical moisture level. However, material characteristics have a major influence in fungus development and were taken into account while categorizing construction materials in this research.

We used a method in which samples with a rating of 2 or higher were considered to have failed and were not further investigated in order to characterize the course of growth and the time at which the threshold moisture level was reached. This method of evaluating a material's resistance to development enables the creation of criteria for what constitutes acceptable behavior in practice. These results may be used to evaluate the mold resistance of novel materials at varying amounts of moisture. After determining the substrate's critical relative humidity, the manufacturer/architect may choose the right material to reduce the risk of mould development, taking into consideration the anticipated temperature and relative humidity conditions.

We acknowledge that our study has a number of limitations. As a result, this test cannot be used to forecast the duration of exposure to a substance beyond the period specified in the laboratory. Such predictions need further study. All of these variables vary across trials, including the fungus, the inoculation technique, the temperature, the relative humidity, the time, the analytical method, and the analysis frequency. To achieve the intended outcome in this research, the advantages and disadvantages of all prior studies and studies in this area were thoroughly examined. Numerous these factors have an effect on the critical moisture level given to a material based on the facts and experiences discussed in this section. The test in this research was done at a constant temperature of 22 ° C and a constant relative humidity. Hydrothermal conditions, on the other hand, vary inside structures. It has an effect on mold development (Nielsen 2004, Viitanen 2004). Even yet, there is a potential of contamination, which may impair mould development. Additional study is required to make such forecasts. It is essential to check the material at a range of different humidity and variety of different moisture levels to determine its critical moisture content.

It is necessary to establish the critical relative humidity of building materials in order to assess their resistance to fungal growth. Numerous factors influenced a building material's critical relative humidity. In this study, temperature, relative humidity, substrate categories, incubation period, and evaluation criteria for mould development have been analyzed. Due to the fact that different substrate categories exhibit variable degrees of fungal resistance, each substrate category must be evaluated individually. In this context, a critical relative humidity was determined for each category according to the results of the experiments conducted in this study. Temperature is also a factor to consider when describing critical Relative humidity. When the temperature decreases, the mold's relative humidity requirement should be higher. This study investigated fungal growth at a temperature of only 22 ° C. Further research is necessary

to make such predictions, as well as to verify whether laboratory tests accurately reflect real-world conditions and how duration affects the outcome.

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No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The first author contributed 60%, the second author 20% and the third auther 20%.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of Karaelmas Science and engineering Journal in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Karaelmas Science and engineering Journal and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Karaelmas Science and engineering Journal.

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